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CHARACTERISTICS OF SELF-EXCITED MOVING STRIATIONS AND

ELECTRIC FIELDS IN A NEON PLASMA

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ABSTRACT

Wavelengths and frequencies of self-excited moving striations in the plasma of a Neon discharge were measured; from this data their velocities were calculated. Measurements were performed in cylindrical Pyrex discharge tubes of inner diameters 4, 10, 31, 75, and 140 millimeters over a pressure range of about 35 to 10,000 millitorr and a discharge current range of about 20 to 400 milliamps. In the 10, 31, and 75 millimeter tubes the average electric field of the plasma was measured under these same conditions. Wavelengths always increased with tube radius, generally decreased as pressure increased, appeared independent of current, and showed an exponential decrease as a function of the parameter, pressure times current density. With the exception of the 4 millimeter discharge tube, frequency generally decreased as radius or pressure increased and appeared relatively insensitive to current changes: in that tube frequency patterns were often erratic. Velocity decreased with pressure and seemed unrelated to radius or current. The electric field decreased linearly with the logarithm of increasing radius, generally decreased as current increased and followed no consistent pattern with pressure. Probes inserted into the plasma for electric field measurements generally caused both striation wavelength and frequency to decrease.

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TABLE OF SYMBOLS

SYMBOL	MEANING
	Wavelength, usually in centimeters
	Frequency, Hertz (cycles/second)
	Velocity, centimeters/second
i	Current, usually in milliamps
p	Pressure, usually in millitorr
E	Electric field, volts/centimeter
K	Constant of proportionality, value defined in the text
R	Radius

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I. INTRODUCTION

The original purpose of this study was to find what effect discharge tube radius had on the wavelengths of self-excited moving striations in Neon. To accomplish this, five cylindrical discharge tubes with radii of 2, 5 15.5, 37.5, and 70 millimeters were selected. Each was operated over a pressure range of about 20 to 10,000 millitorr and a current range of 20 to 400 milliamps. As the plan for the work was formulated it became obvious that for little more effort, much more information could be obtained about these striations' natural frequencies and velocities of propagation as well as the positive column's electric field gradient, over these same geometrical, pressure, and current ranges. The necessary equipment was accordingly added.

The final effect studied was that which the physical presence of probes (used to determine the electric field gradient) in the discharge tube have on the moving striation variables. This latter study seemed appropriate since one would logically expect some perturbations of the striation wave train because of the finite, though small, portion of the positive column cross section occupied by a probe.

As is well known, the primary problem in developing useable data on this subject is that for a given gas there are three major independent parameters that effect the dependent variables subjected to study. A single change in any one of the parameters of pressure, discharge current, or tube geometry while the other two are held constant, will

cause a change in the striation's characteristics and in the electric field. Ideally for this type of study, we fix the current and pressure at predetermined values, vary the radius and then measure effects. In reality, precise fixing of tube geometry and current to predetermined values is readily accomplished by glassware construction and proper electric circuitry; however, exact, predetermined pressure settings require highly sensitive metering (valves and gauges) and this is not readily found. Even if obtainable, such sensitive metering would probably by its very nature greatly increase experimental time when used in the millitorr range.

Thus we have a four-dimensional problem to cope with where one of the independent dimensions is not easily controlled, and the fourth depends on the other three. As might be expected, the experimental difficulties are trivial compared with the problem of the four-dimensional analysis that must come from it.

The accumulated experimental data rapidly became so voluminous that the author decided to code it so that the electronic computer at this school could assist in the analysis. This proved to be exceedingly useful: calculations, graphical displays, and other analyses that would have taken many months to perform manually were accomplished in two weeks. Total computer time was less than two hours, exclusive of graph plotting. The latter was done "off-line" by other automated equipment based upon information generated by the computer and fed to the other equipment on magnetic tape.

II. REVIEW OF PREVIOUS WORK

A. General

The phenomena of moving striations in the positive column of a gas discharge at low pressure has been studied for many years. In researching published literature as well as an excellent review of the literature, "Moving Striations" by Oleson and Cooper (1) (soon to be published), one gets the distinct impression that there has been relatively little study in recent years on the basic characteristics of self-excited striations, i.e. wavelength, frequency, and velocity. The more sophisticated areas such as those concerning the phenomena of artifically excited striations seem to be holding current interest. In fact Pupp's papers (2) in the early nineteen-thirties, still can be considered as a major work in this fundamental area. But even his papers leave much unanswered concerning the basic relationships between the variables associated with self-excited moving striations.

As discussed in the introduction, the measurable quantities characteristic of these striations are so dependent on three parameters that there exist no simple cause and effect relationships. This probably is a contributing factor to the paucity of recent work in this area. As an aside thought: it may well turn out that the cause and effect relationships will prove to be so non-linear, even to the point of being erratic, that once they are experimentally determined one would be hard pressed to develop the theory that explains them.

When earlier researchers found this lack of two-variable linear relationships, they then combined sets of variables in an attempt to find correlations (2, 3). Pupp, for example, found that plots of frequency times tube radius versus pressure times tube radius fell on a curve independent of radius and current. As will be discussed in section VI, results of this study indicate that the curve may in fact be a banded area of finite width rather than a thin-line type of curve.

B. Striation Wavelength

Druyvesteyn (4) found that the wavelength of striations in rare gases involved a relationship $\lambda/R = f(pR, i/R)$ where "f" signifies function and not frequency.

More recently, Kenjo and Hatta (5) found in Neon that

$$\lambda \propto R^N \qquad 1.5 \leq N \leq 2.0 \qquad 1.$$

This was determined by using a tapered discharge tube. Although they did not report their ranges of discharge current and pressure, some of their published graphs indicate their ranges are encompassed by those of this work. Extrapolating from their published graphs one finds that their empirical equation is likely to be

$$\lambda \cong KR^N \qquad 2.$$

where K is a constant of proportionality approximately equal to 5. It must be noted that these authors did not publish the relation given by equation number 2, but only the proportionality given by equation number 1. The proportionality constant K was arrived at by taking a mean value of 1.75 for N and fitting their published data to the relationship.

In the case of Argon, work by Alexeff and Jones (6) agreed reasonably well with portions of Kenjo and Hatta's theories, when they used a similar size and shaped discharge tube. However, Alexeff and Jones found little dependence of wavelength on radius at the pressure extremes.

Kenjo and Hatta made a point of basing part of the validity of their relationship on the theory that only a single tapered tube should be used to determine the $\lambda = f(R)$ equation. They state that "to use many cylindrical tubes with various radii is not preferable to obtain this relation, because the mode of each tube is not always the same." However, in the present investigation an attempt was made to overcome this objection by keeping all other parameters the same.

As will be discussed in detail later, results of this work agree only partially with the theory of Kenjo and Hatta. The theory appears to fail noticeably when applied to very large and very small radii.

C. Striation Frequency

Pupp's findings, mentioned earlier, that the quantity frequency times radius versus the quantity pressure times radius yields a smooth curve, has since been observed several times (for example: Oleson and Cooper (7), Donahue and Dieke (3)).

For the effect of tube radius on frequency, Oleson and Cooper (7), and Alexeff and Jones (6) have found that frequency increases when the tube radius decreases.

In section VI, it is shown that the results of this study agree fairly well with this generalization if data taken from tubes of small radii (5 millimeters or less) at low pressures (about 200 millitorr or less) are not included. Again we see the problem that arises when we attempt to relate a dependent variable to only one of the independent parameters.

D. Striation Velocity

Alexeff and Jones (6) found experimentally that at low pressures (10 millitorr and less), the velocity was not related to discharge tube radius, while at higher pressures, it seemed to be a function of radius. They further noted a rapid decrease in velocity as the pressure was increased. Results of this study support the latter finding, but no clear-cut relation between velocity and radius was found.

Others, such as Oleson and Cooper (7), and Kenjo and Hatta (5) have found that velocities generally increased as tube diameter decreased.

E. Electric Field Gradient

Druyvesteyn (4) noted that in general the electric field was inversely related to the discharge current. He also found it inversely related to tube radius until tubes of "large" (unspecified) radii were used, in which case the electric field was no longer a function of radius. This study does not completely support that last statement in that the electric field was still related inversely to radius out to a radius of 37.5 millimeters (the 75 millimeter tube).

Güntherschulze (8) stated that in "wide" discharge tubes the electric field was no longer a function of pressure and he called this situation "the normal gradient." If a 75 millimeter discharge tube can be classified as "wide" this study shows a strong non-linear dependence of the electric field on pressure through a wide range of radii.

More recently, Alexeff and Jones (6) found the electric field to be "remarkably constant" and not a function of radius. (This study does not at all support that statement.) Opposed to their findings is that of Kenjo and Hatta (5) that in a tapered tube $E \sim 4/R$.

Oleson and Cooper summarized the situation with their observation (1) that "further experimentation is required to resolve this point" (of obvious disagreement) on the effects that tube radius has on electric field.

Also of interest is the relation found by Novák (9)

$$\lambda = \phi_i / E \qquad 3.$$

where ϕ_i is a constant, independent of current, pressure and tube diameter, but dependent upon the type of gas in the discharge. Data in this study agreed with the idea of linearity shown by the equation. However, a sharp discontinuity in the region of E = 2 volt/centimeter, λ = 12 centimeters, seems to imply that there are in fact more than one constant of proportionality, ϕ_i, and that they appear to be related to discharge tube radius. This is discussed further in section VI.

F. Probe Perturbations

No published works were found that discussed the perturbing effects that the physical presence of probes in a discharge tube have on the basic characteristics of self-excited striations.

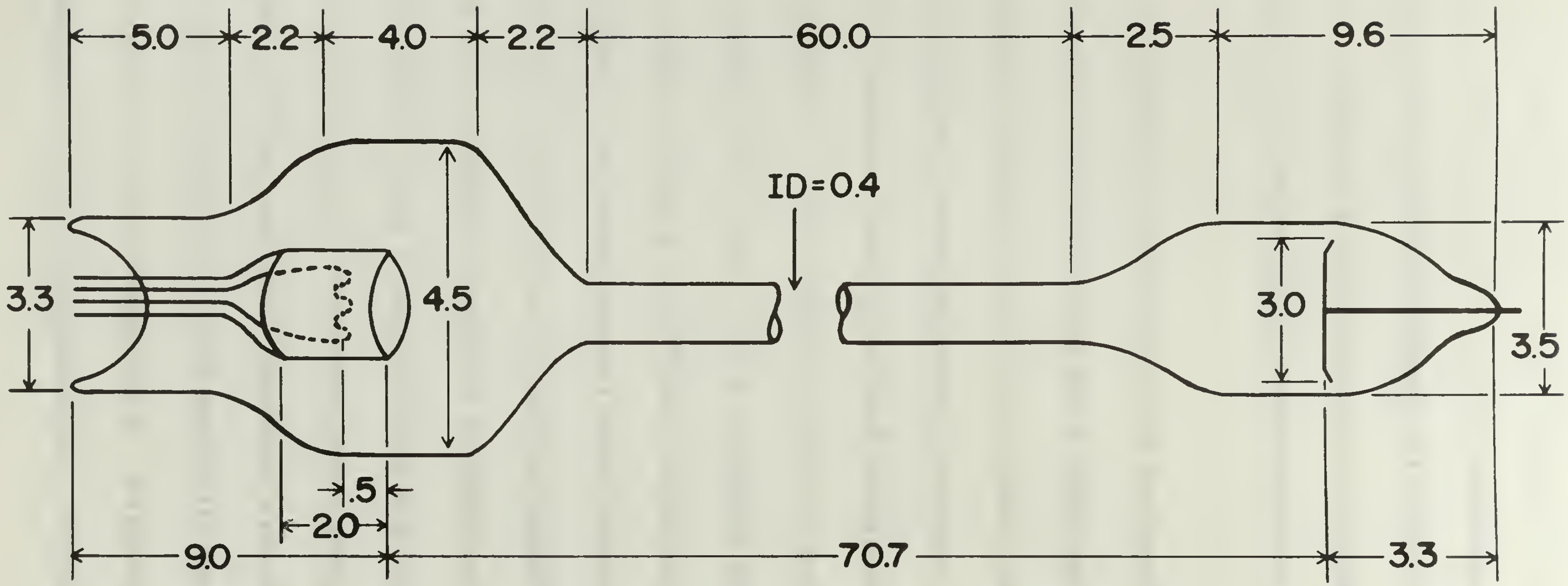
III. EQUIPMENT

A. Experimental Apparatus

This section describes the equipment and circuits used in this study of self-excited striations' frequencies and wavelengths in a Neon plasma. In addition to the detailed description below are line drawings in Figures 1 through 5.

1. Vacuum System and Pressure Measuring Equipment

The discharge tubes were operated directly connected to the evacuation and filling system to allow rapid variation in gas pressure. A common vacuum, gas reservoir, and manometer system was used for all discharge tubes. This system had the proven advantage of rapid pumping speed after baking out with a portable oven. For example, the system could be evacuated to about 1×10^{-6} Torr in less than one minute after being operated in the 1 to 10 Torr pressure region. This advantage was quite useful due to the frequent pressure changes required in amassing data. Ultimate pressures on the order of 1×10^{-8} Torr were attained after several hours of continuous pumping. The entire system except manometer, gas reservoir and a part of the glass tubing and valve leading to the pumps were baked with a portable oven each time a new discharge tube was installed. Bakeouts lasted for about six hours, either at 410°C with all valves open or at 250°C if a new gas reservoir had not been installed. In the latter case, the control valve to the reservoir remained shut, necessitating the lower temperature.



DIMENSIONS IN CENTIMETERS

Figure 1. 4 millimeter discharge tube.

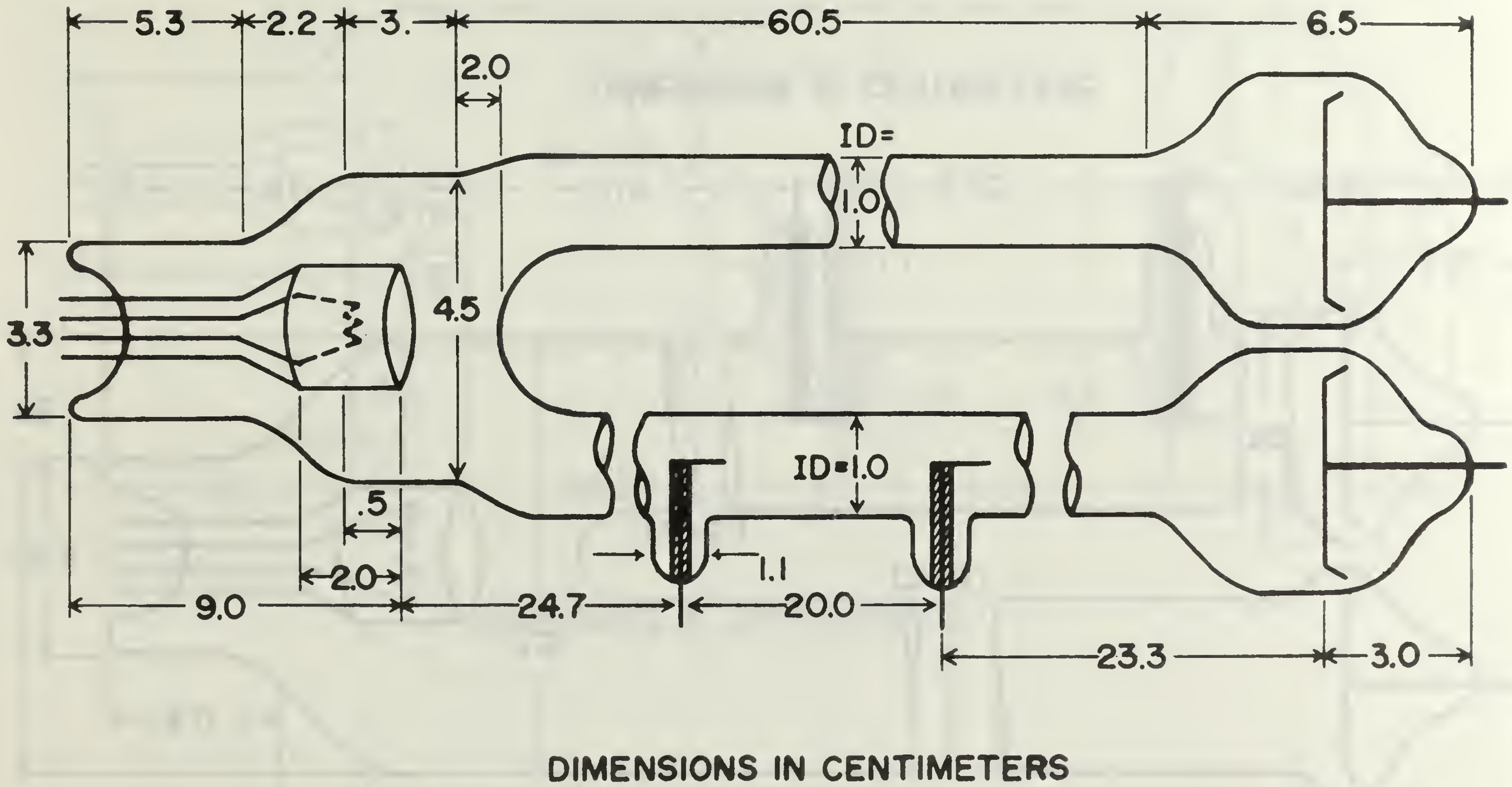


Figure 2. 10 millimeter discharge tube.

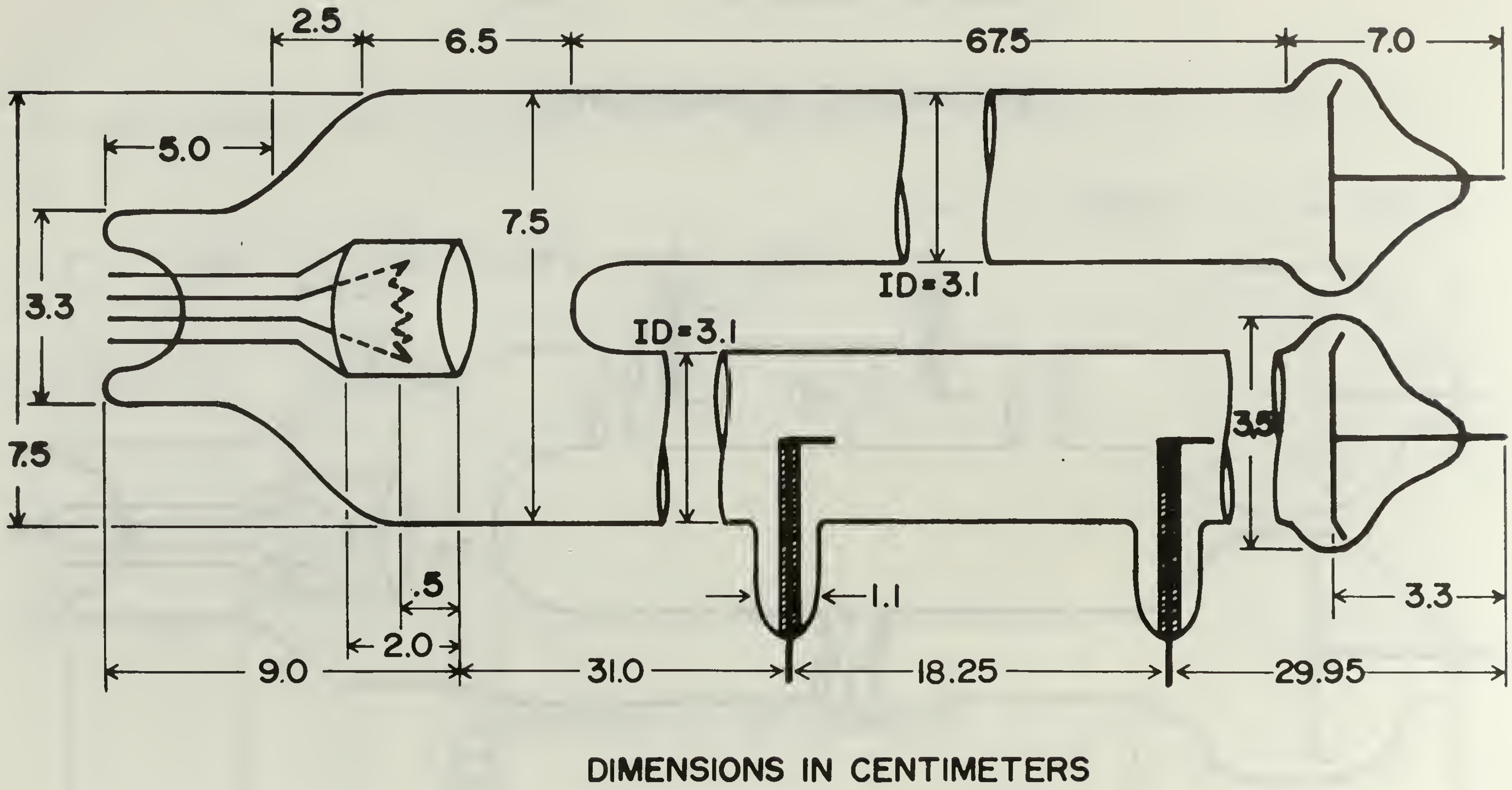


Figure 3. 31 millimeter discharge tube.

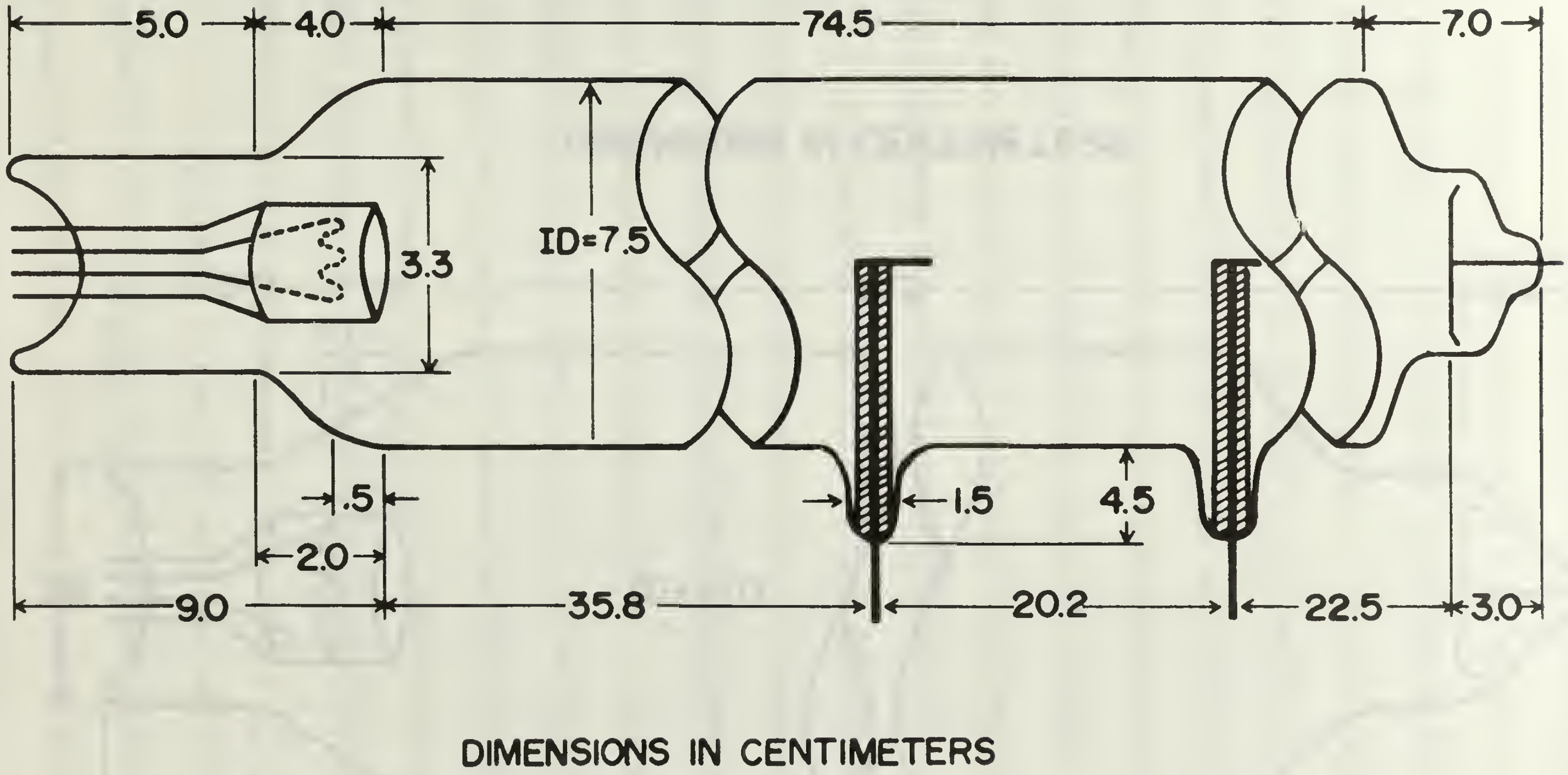


Figure 4. 75 millimeter discharge tube.

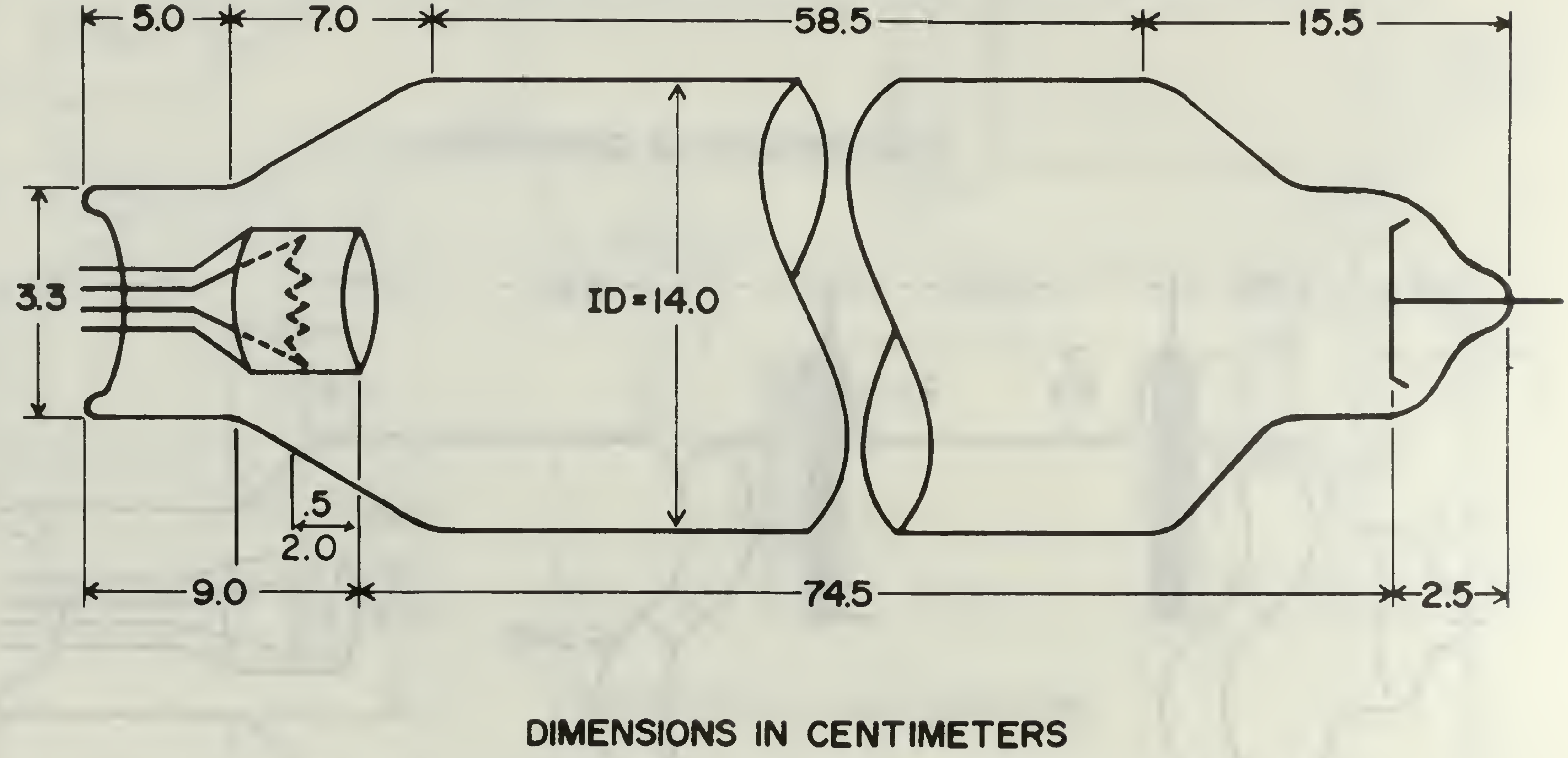


Figure 5. 140 millimeter discharge tube.

The system was evacuated with a Veeco EP2-1, two-inch metal diffusion pump (speed 80 l/sec) and a Cenco Hyvac Model 14 fore-pump. The diffusion pump was trapped with an AeroVac Model AT2F liquid nitrogen trap. The connection to the rest of the system was via glass tubing through a General Electric 1-1/2 inch bakeable valve. The discharge tube and one inch diameter glass tubing lines connecting the reservoir and manometer to the system were mounted above an asbestos table top which accommodated the portable oven during bake-out. Valves exposed to this baking were Granville-Phillips 1/2 inch valves. A Linde one-liter flask of Neon constituted the reservoir and was changed with the installation of every other discharge tube.

Pressures less than 10^{-4} Torr were measured with a NRC 563-P ionization gauge connected to a Veeco Vacuum Gauge Controller, type RG-2A. Pressures in the operating range of 20 to 10,000 millitorr were determined by an oil-filled manometer as read with a cathetometer at a distance of 20 feet. It was intended that Westinghouse 7903 Ionization (Schultz) Gauge be used for measuring pressures in the lower part of the operating range. However, operational failures in that gauge's ancillary equipment did not permit it to be used within the time frame imposed for this thesis.

Pressures of 1 to 10 Torr were read directly with the oil manometer; its oil's density was such that one centimeteter of displacement equalled 0.672 Torr. For lower pressures we assumed that Neon obeys the Ideal Gas Law and proceeded as follows:

The manometer was filled with Neon to a relatively high pressure so that a large displacement in oil levels was obtained (typically 45 to 50 centimeters). The displacement D_1 was measured with a cathetometer and the pressure P_1 calculated; e.g. 50 cm oil x .672 Torr/cm oil = 34.6 Torr. While this measurement was being made the manometer was closed off from the rest of the system and the system was pumped down to about 10^{-7} Torr. After equilibrium the valve to the pumps was closed and the gas in the manometer allowed to expand into the entire system. Again after equilibrium the second oil displacement, D_2, was read (typically 0.5 to 1.5 centimeters) and converted to a pressure P_2. This procedure was repeated numerous times when a new discharge tube was installed to the system. By averaging the readings, a pressure ratio P_1/P_2 was obtained for each tube plus rest of system, and pressures on the order of 15 to 20 millitorr could be accurately determined. As will be discussed later, at pressures below 100 millitorr, <u>measurable</u> self-excited striations were infrequently encountered during this study.

2. Discharge Tubes

Five discharge tubes of different diameters were used in this work; all made of Pyrex glass. Their inner diameters were 4, 10, 31, 75, and 140 millimeters and overall lengths were between 83 and 90 centimeters. The useable positive column in each was about 60 centimeters long. Diagrams of these tubes and their geometry are shown in Figures 1 through 5.

The 10 millimeter tube consisted of two parallel tubes, one with probes, one without, and joined at a common cathode-filament base. The parallel tubes had separate anodes. The 31 millimeter tube had a similar configuration. The purpose of this geometry was to allow study of the perturbing effects that probes have on self-excited striations. These effects will be discussed later. (Note: Hereafter, when discussing a tube of specific diameter, the singular form "tube" will be used, even though the 10 millimeter and 31 millimeter configurations were in fact each a pair of tubes with a common cathode base.)

In order to maximize common geometry, nearly identical anodes, cathodes and their respective glass housings were used on each tube. Anodes were tantalum disks, 3 centimeters in diameter. See Figure 6. Filaments of all tubes were Westinghouse Style No. 14-39601 coiled ribbon, oxide coated, made of tungsten, rated at 5 volts, 7.5 amperes. Tantulum cylinders surrounding the filaments served as shields.

Two fixed probes made of 20-mil tungsten rod were installed in one member of the 10 millimeter pair and 31 millimeter pair of tubes, and in the 75 millimeter tube. These probes were spaced about 20 centimeters apart and approximately centered about the mid-length of each tube. See Figures 2 through 4. Inside the tube the end of each probe was bent through 90 degrees so that about one-quarter of an inch of each probe lay along the axial center of the tube with probe tips facing the anode. The remainder of the probe was sheathed with an alumina tubing sleeve. See Figure 7. This construction technique had

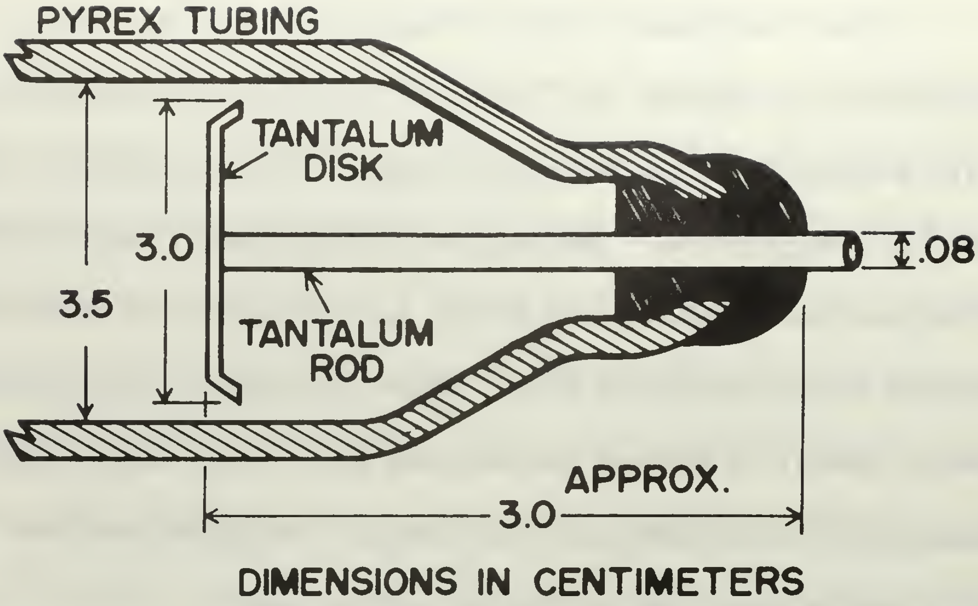


Figure 6. Anode construction.

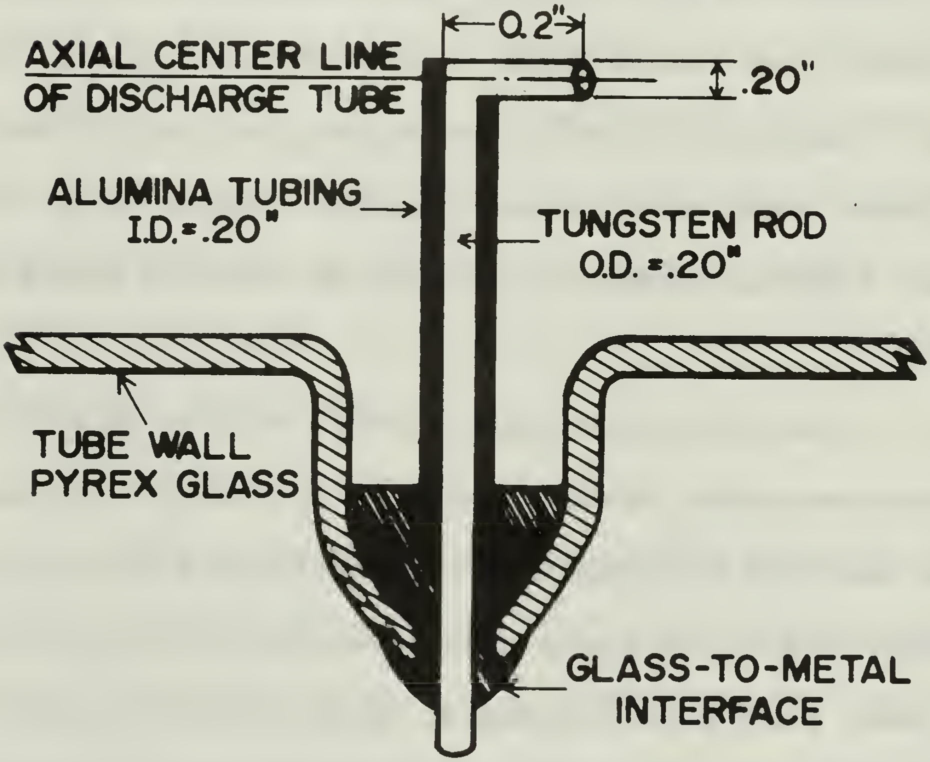


Figure 7. Probe installation.

been previously shown to reduce spattered probe deposits and allows more accurate measurement of the average axial plasma electric field. (10)

The small girth of the 4 millimeter tube did not allow probes to be installed in it. Several attempts by a highly skilled glass-blower to install probes in the 140 millimeter tube failed. The large surface area of this tube would not allow controlled annealing to take place after probe installation: hence the tube always fissured during cooling.

3. Discharge Tube Circuits

The filament power supply and the main discharge power supply were common for all tubes. See Figure 8. The discharge tube filament was operated by a diode rectifier, filtered 9 volt power supply which was controlled by an autotransformer.

Discharge tube current was controlled by the voltage of the main power supply which was connected through two 2580 ohm, 0.5 amp rheostats in series, to the discharge tube. This power supply was a locally constructed 0-5 kilovolt, 0-1 ampere, direct current, unregulated, filtered supply with output voltage controlled by an autotransformer on the input of the supply. In addition to the built-in ammeter and voltmeter of the power supply, more accurate instruments for measuring these parameters were in the circuit and will be discussed in the Diagnostic System Section.

4. Diagnostic System

a. Striation wavelength-measuring equipment

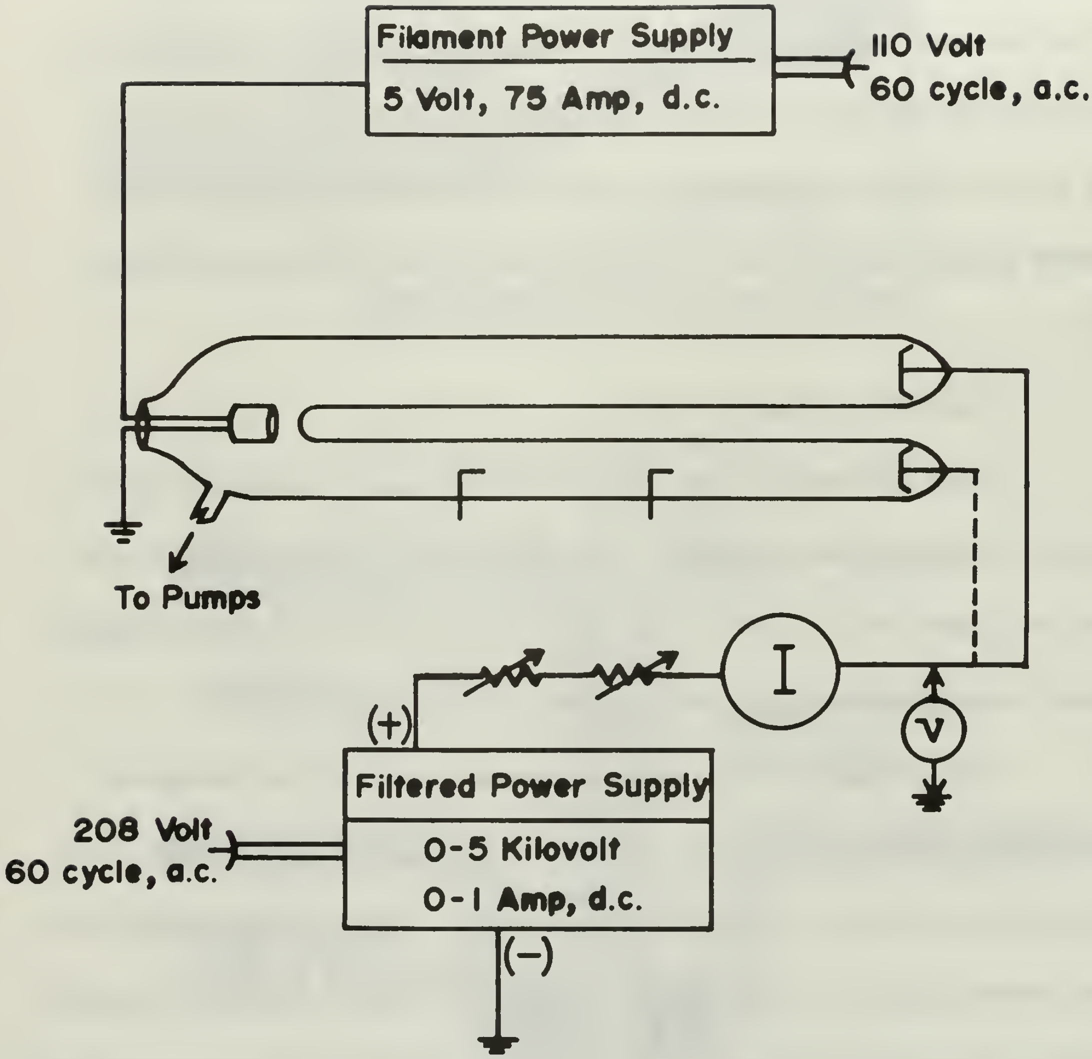


Figure 8. Power supply, all discharge tubes.

The original purpose of this study was to determine what effect, if any, discharge tube diameter (or radius) had on direct current self-excited striations in a plasma. Accordingly two RCA 1P22 photomultiplier (hereafter PM) tubes and a Tektronix Type 555 Dual Beam Oscilloscope formed the heart of the diagnostic system.

This equipment was arranged so that the output signal of a reference PM tube externally triggered the sweep of the oscilloscope which displayed the output signal of the second movable PM tube as well as that of the reference tube. See Figure 9. The PM tubes had a common power supply which was locally constructed, having a 1200 volt, 1 milliamp output. Each tube was mounted on a simple sliding truck which in turn fitted on an aluminum track. The track was graduated with a millimeter scale and was situated parallel to the discharge tube. By observing the oscilloscope display of the second PM tube while moving the tube along the length of the discharge tube, direct wavelength measurements could be taken. Light from the plasma discharge to the PM tubes was collimated by two slit-type baffles installed in a collimating tube locally constructed from 6-ounce frozen juice cans. All other light was blocked from the tubes.

b. Striation frequency-measuring equipment

The signal output from the movable PM tube was also used to activate a Hewlett-Packard Electronic Counter, Model 521A. From a "T" connector at the oscilloscope, the signal went through a Scott Decade Amplifier Type 140A set for 100-fold amplification, and

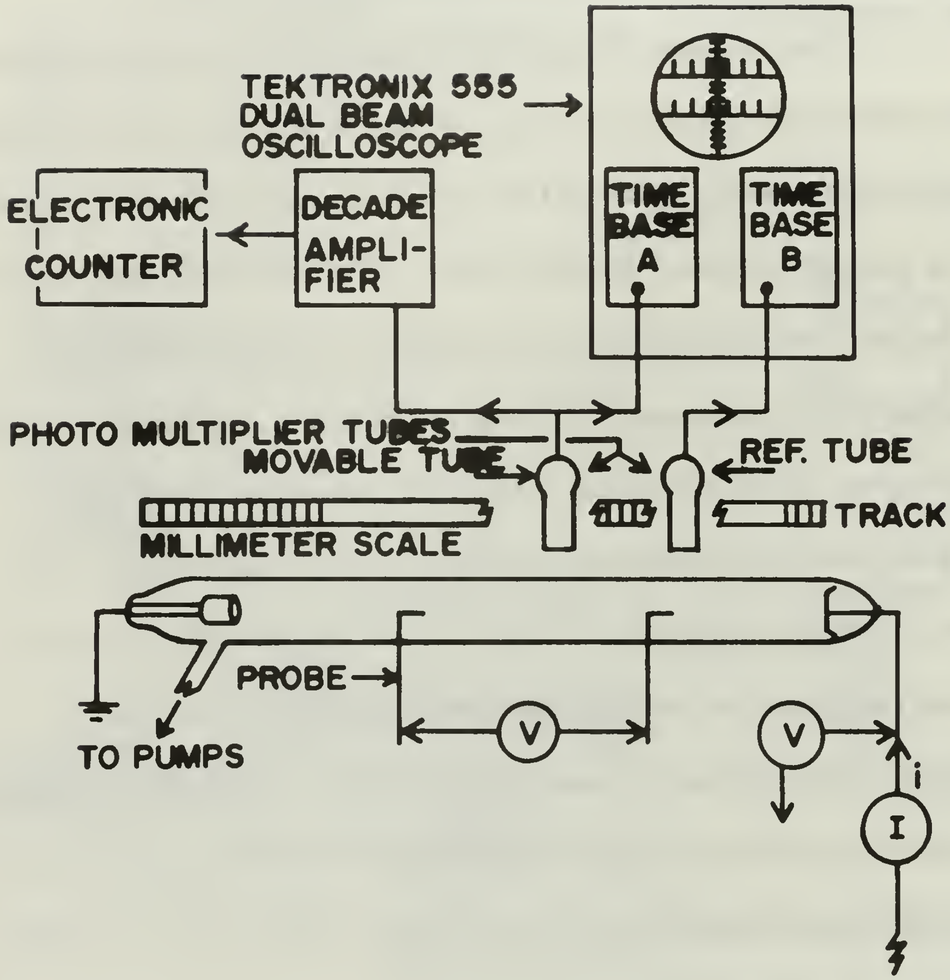


Figure 9. Diagnostic system. Probes in 10, 31, 75 millimeter tubes only.

thence to the counter. See Figure 9. This technique gave direct frequency measurements. Hence it was considerably more time saving as well as inherently more accurate than measuring the length of the signal wavelength on the oscilloscope reticle and converting that measurement to a frequency by means of the time base setting.

c. Electric field measurements

These data were calculated by measuring the voltage potential difference between the fixed probes installed in the 10, 31, and 75 millimeter tubes, and dividing this measurement by the distance between the probes. This gave the average electric field values.

During the initial stages of the study, the voltage was measured with a high impedance Keithley Vacuum Tube Electrometer Model 600A. In spite of the fact that shielded cable leads connected the probes to the electrometer (used on voltmeter setting) considerable time was lost waiting for the meter to overcome "drift" effects each time it was connected across the probes. Further, the slightest movement of leads, or even the routine motions of the observer reading and recording data, caused fluctuations in this highly sensitive instrument. In an attempt to overcome this unacceptable and continuing time loss, a Simpson Multimeter on voltmeter setting was tried out. This meter had a sensitivity rating of 5000 ohms per volt in the voltage range utilized.

Under carefully controlled and identical conditions, the Simpson Multimeter was found to give voltage readings within 2% of those of the Keithley Electrometer when they were compared for probe

voltage measurements. These tests were made on the probe system in the voltage range encountered in this work, i.e. 80 to 150 volts. Also no other variables such as discharge current changed when one meter was substituted for the other. Since there was a negligible time lag involved with the Simpson meter, it was used for the remainder of the study to measure the voltage between probes.

In order that there would be no possible perturbing effects, the voltmeter was connected across the probes only for the voltage measurement. It was then removed before the next wavelength or frequency measurement was taken.

d. Discharge tube voltage and current measurements

A RCA Senior Voltohmyst Vacuum Tube Meter was used to measure the anode-cathode voltage drop. Since the cathode was at ground potential and often more than 1500 volts initial potential difference across the discharge tube was required to establish the plasma, this voltmeter was connected across the tube after the discharge was activated. In this way the voltmeter's capacity was not exceeded. After that, so long as there was a discharge, this meter was not disconnected during data taking.

Even though high voltages were often required to maintain the discharge, the current through the discharge was not allowed to exceed 400 milliamps; hence the ammeter used was never disconnected from the circuit. For currents of less than 100 milliamps, a milliammeter of finer scale was placed in the circuit. When taking

data, the current was varied in 20 or 30 milliamp increments from 20 to 400 milliamps by adjusting the rheostats in series. Occasionally, the main power supply voltage output had to be increased to get the 20 to 400 milliamp current range.

B. Data Analysis Equipment

In the course of this experiment more than 5000 items of data were taken. Due to the myriad of ways that this data, together with results calculated from it, could be arranged, the Postgraduate School's Control Data Corporation (CDC) 1604 Computer was used to assist in the analysis.

A data card was made for each observation of wavelength and frequency. Also coded on this card were: tube diameter, probe spacing distance, pressure and discharge current in the tube at the time of the observation, anode-cathode voltage difference, and the voltage difference between the probes. In the case of the 10 and 31 millimeter tubes, the frequency and wavelength in the adjacent tube under identical conditions were coded on the same data card. Figure 10 shows a sample data card.

Results of calculations with these data were graphed, when applicable, by a CalComp 165 Plotter which was operated "off-line" from the CDC 1604 computer. The methods of data analysis are discussed in section V.

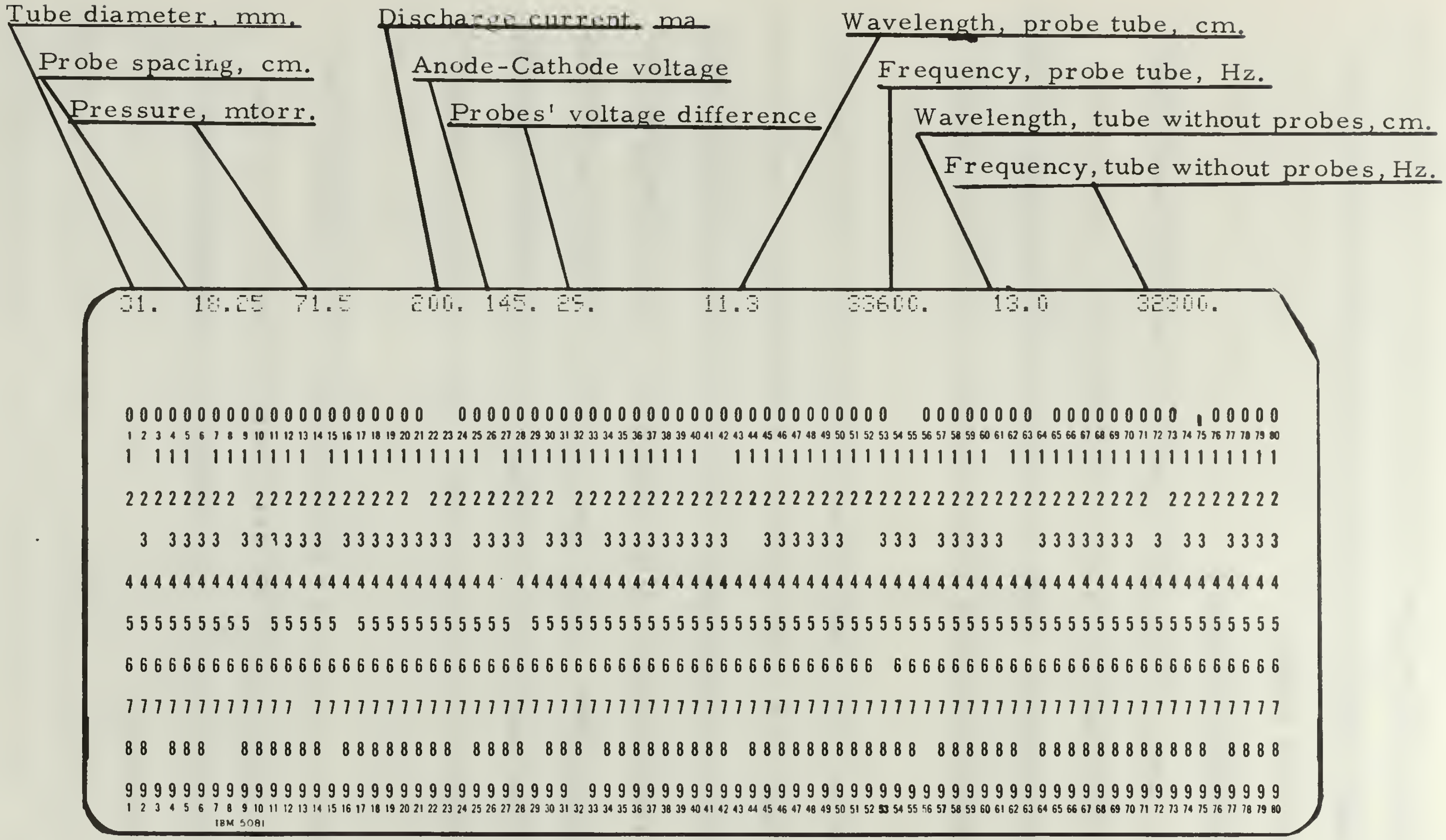


Figure 10. Sample data card. Experimental data coded as indicated.

IV. EXPERIMENTAL TECHNIQUE

A. Preparation for Data Taking

As is frequently done, the two parameters of gas pressure and discharge current were varied, and the resulting striation frequencies and wavelengths, as well as pertinent voltages recorded. After the system had been baked out but before taking any measurements the following took place:

1. The system and oil manometer were evacuated to a very low pressure (on the order of 10^{-7} Torr) and gauge and filament outgassed.

2. To reduce "clean-up" effects the tube was filled with Neon to a pressure in the vicinity where data was to be taken and a discharge operated for several minutes at a current of about 250 milliamps.

3. While the discharge was maintained the system was again evacuated. When the discharge flickered out during this pump down, the main voltage supply to the anode and cathode was turned off, but the filament left on at its operating current.

4. When a pressure of about 10^{-7} Torr was again reached (usually in a very few minutes) the valve to the pumps was closed.

In this manner the system was purged prior to each series of measurements at a given pressure.

B. Measurements

1. General

The system was again filled with Neon to the approximate desired pressure. A discharge was established and the current increased in 20 or 30 milliamp increments over a range of 20 to 400 milliamps. At each increment the discharge was allowed to reach a steady state before measurements were taken.

As is well known, self-excited striations are not present at all pressures between 10 and 10,000 millitorr, nor are they always present at all currents between 20 and 400 milliamps for a fixed pressure in that range.

Accordingly, this investigator started taking data on each tube at a pressure of 8,000 to 10,000 millitorr if coherent striations were present at this high a pressure. When such striations were found at a selected pressure, the current was then varied over the operating range and data taken.

If coherent striations were readily found in a particular pressure range, once data had been taken at one pressure, the system was evacuated, purged, and refilled to a pressure about one-fifth lower. The overall plan was to take data at pressures of about 10,000, 8000, 6000, etc., 1000, 800, 600, etc., and 100, 80, 60, etc. millitorr.

Whenever a pressure region that would not support coherent self-excited striations was encountered in this downward trend of pressure, the pressure was gradually reduced until the next useful region was found. This explains the large gaps in pressure to be noted in examining data and results in this thesis.

In this manner the pressure was stepwise reduced until measurable coherent striations were no longer to be found. At pressures lower than these, the positive column still existed but no useful data could be obtained due to the "noise" of the discharge. Possibly one of the limiting factors in this regard was the spectrum sensitivity of the PM tubes used in measuring wavelength and frequency. At very low pressures (less than 100 millitorr) for all but the 140 millimeter tube, the discharge gradually changed colors from its distinctive "neon red" to a whitish-orange. In the case of the 140 millimeter tube the color changed through shades of purple to a light lavender. It may be that a PM tube more sensitive to yellow-orange than red will be able to discern any self-excited striations present at these low pressures. However, since coherent moving striations also depend upon the length of the discharge tube (1) there may be none present at these low pressures in such relatively long tubes as used in this work.

It was noticed that in general measurable striations are more pressure sensitive than current sensitive in these operating ranges. Usually striations could be found over most of the current range once the pressure was in a satisfactory region. On a few occasions at unsatisfactory (for our purposes) pressures, stabilized striations were found if the current range were increased to 1 amp. However, the electrical components of this system would not permit any sustained operation at currents greater than 500 milliamps since that was their rated maximum. Further, heat dissipation was a problem for this

system when it was operated at currents greater than 350 milliamps. Therefore this interesting side-line was not pursued.

2. Pressure Measurements

As discussed in section III, pressure was measured with an oil manometer as read by a cathetometer at a distance of 20 feet. In the 1000 to 10000 millitorr range the pressure in the system was read directly. For pressures less than 1000 millitorr, the gas expansion technique described in section III was employed.

3. Wavelength Measurements

The two PM tubes were used to measure the wavelength. These tubes were placed side by side on their truck mounts, so that their apertures were close to the discharge tube. As described previously the signal output of one tube (reference) was used to trigger the sweep of one of the beams of the dual beam oscilloscope while being simultaneously displayed on the other beam. The signal from the second (movable) PM tube was displayed on the triggered beam.

First, the waveform and phase of the triggered display were noted. The second PM tube was then moved down the length of the discharge tube until the phase of the waveform became the same as in the original position. This indicated that the distance travelled by the PM tube was just one wavelength. This distance was measured directly using the millimeter scale attached to the track which held the trucks of the PM tubes.

Whenever possible, wavelength measurements were taken from a starting point about 15 centimeters from the anode end of the discharge tube and measured toward the cathode. However, for the 140 millimeter tube (and occasionally the 75 millimeter tube) the cathode fall region (dark space...no positive column present) extended from the cathode toward the anode for about one-third the distance between the two. And for this tube, wavelengths between 30 and 40 centimeters were often found. Therefore, the starting point for measuring wavelengths was moved to about 5 centimeters from the anode in order that the wavelength to be measured was "contained" in the positive column that could be seen by the PM tube.

4. Frequency Measurements

The signal from the PM tube that measured wavelength also triggered the electronic counter that measured the frequency. These measurements were taken at the point along the discharge tube that marked the starting point of the wavelength measurement.

The display time of the counter was set so that a frequency count was displayed every second. For frequencies less than 10,000 Hertz, the count rarely varied more than 2 per second for any pressure-current combination. However at higher frequencies the counts sometimes varied by $\pm$ 3% from the mean. In these cases, about 10 consecutive counts were averaged to obtain the mean frequency for the pressure-current combination.

After the frequency and wavelength had been measured in the probe-free tube of the 10 and 31 millimeter pairs, the PM tubes were depressed into position to make the measurements in the probe tubes.

While a discharge was operating in one of the members of the pair, none was operated in the other to avoid the possibility that radiation from one tube might perturb the plasma constituents in the other while the latter were being observed.

5. Electric Field Determination

The average electric field was calculated (one of the jobs of the CDC 1604 Computer) from the voltage measurements made between the fixed probes in the 10, 31, and 75 millimeter discharge tubes.

As mentioned in section III, voltage measurements were made initially by a Keithley Electrometer and later by a Simpson Multimeter. The distance between the probes had been previously measured. The computer merely divided the measured voltage by the inner-probe distance to obtain the electric field strength.

6. Discharge Current and Voltage

The current of the discharge, along with the pressure, was a variable parameter that fixed the values of the parameters. Two laboratory ammeters were used in this study. For currents less than 100 milliamps, a milliammeter graduated in 5-milliamp intervals was used; for 100 milliamps and greater, a 0-1 amp ammeter, graduated in 10 milliamp intervals was used.

Discharge voltage was measured between anode and cathode (anode was positive; cathode was at ground potential) by a vacuum tube voltmeter. The original purpose of this measurement was to provide a check that identical electrical conditions existed in the members of the 10 and 31 millimeter tube pairs (after assuring that identical currents passed through each tube). Hence, at the same pressure, any striation wavelength or frequency difference between pair members could be attributed to the presence of probes in one of them.

V. METHOD OF DATA ANALYSIS

Coded data cards as illustrated in Figure 10 were prepared for every measurable striation wavelength observed while incrementing pressure and discharge current. As previously mentioned, frequency, current, voltages and pressure at the occurrence of the striation were also included on the data card, as well as the tube's geometry. This information was then fed into the Postgraduate School's CDC 1604 Computer along with necessary program and control cards. Desired calculations were then performed by the computer and results printed out and/or graphed for study. A flow chart showing the basic program structure is illustrated in Figure 11.

For initial analyses, data cards were segregated by tube size (radius is one of the independent parameters) and then further sorted into groups of like pressure or like current. The program then had the computer make calculations, e.g., electric field and striation velocities, for print out. Finally these calculations as well as portions of the input variables were plotted as functions of the independent parameters. Typical results are shown in Figures 12 through 16. In this manner, the types of graphs shown on the next page were made.

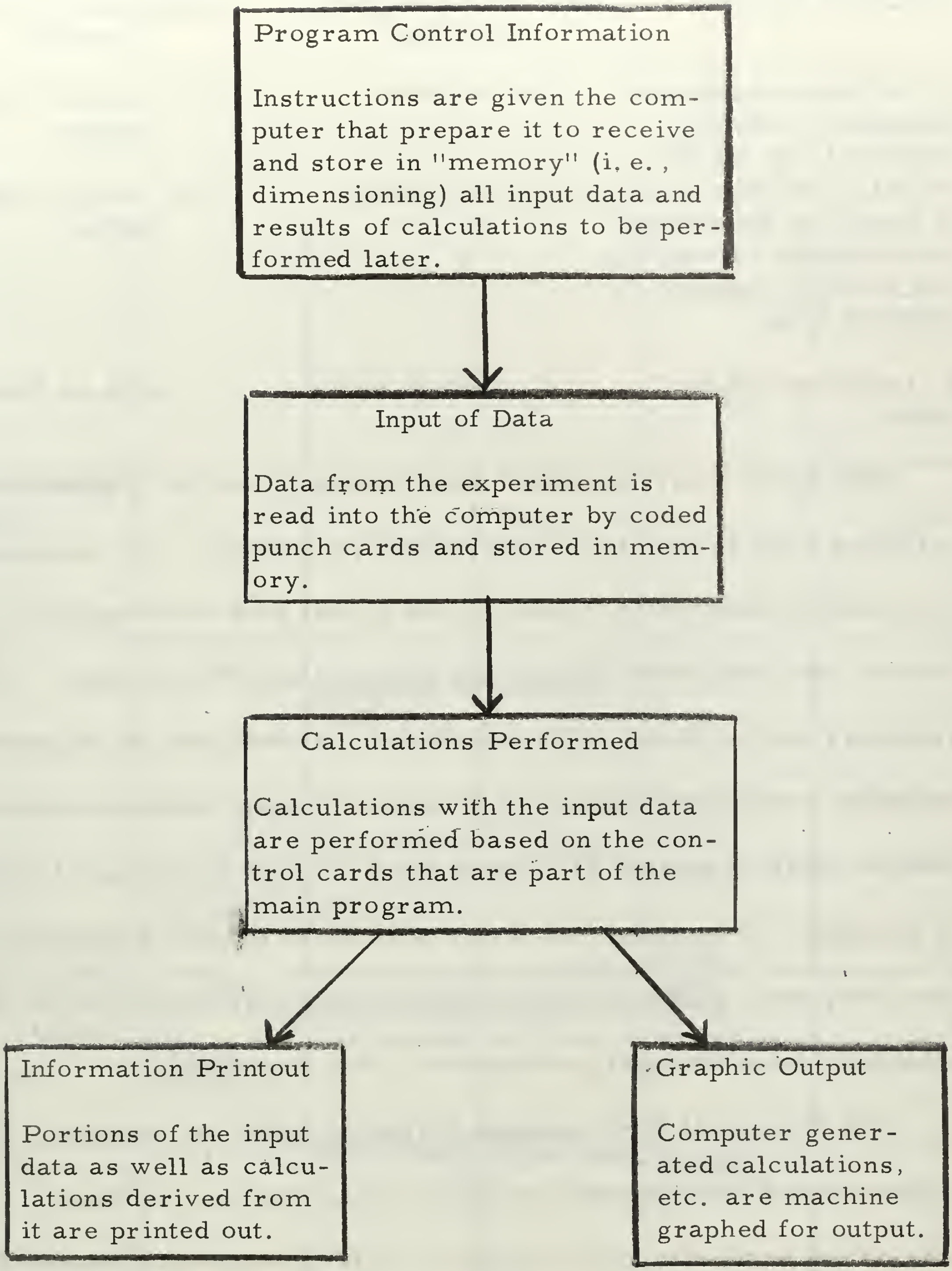


Figure 11. Computer program flow chart.

dependent variable	independent parameter (varying)	independent parameter (constant)
1. striation wavelength, frequency, velocity, electric field; for the 10 and 31 millimeter pairs of tubes: the differences in wavelength, frequency, and velocity, between adjacent tubes.	1. a. current 1. b. pressure	1. a. pressure and radius 1. b. current and radius
2. logarithms of the above	2. same as above	2. same as above

This initial analysis showed many trends on how the dependent variables were related to the independent parameters. For example, it is readily observed in Figures 12 and 13 that both wavelength and velocity are independent of currents greater than 100 milliamps. These graphs as well as those in Figures 14 and 15 showed that the dependent variables were quite sensitive to pressure. These trends are discussed in more detail in section VI. There were also cases of unusual behavior to be noted: for example, the frequencies found in the 4 millimeter tube were very much related to the current at certain pressures but at other pressures were not nearly as sensitive. See Figure 16.

Next data on all five tubes was displayed on the same graph. These graphs showed the dependent variables of each tube as functions of pressure at equal discharge currents. This technique is illustrated by Figure 17. Here again obvious trends were noted but no clear-cut relationship of the dependent variables on tube radius alone was found.

In the middle regions of tube radius, pressure, and discharge current, it was found that relationships were often well-behaved.

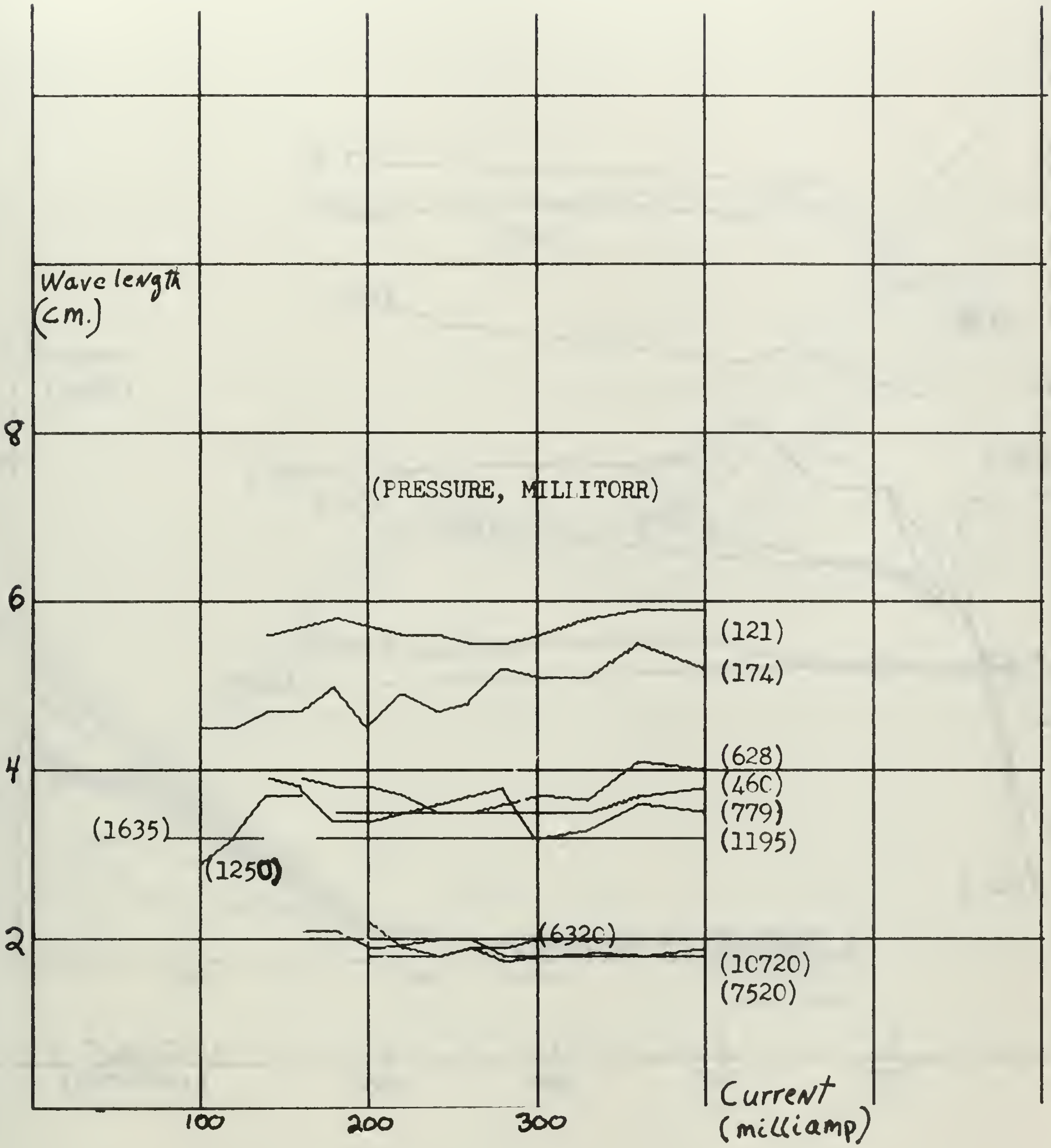


Figure 12. Striation wavelength versus discharge tube current. 10 millimeter discharge tube, common pressure curves.

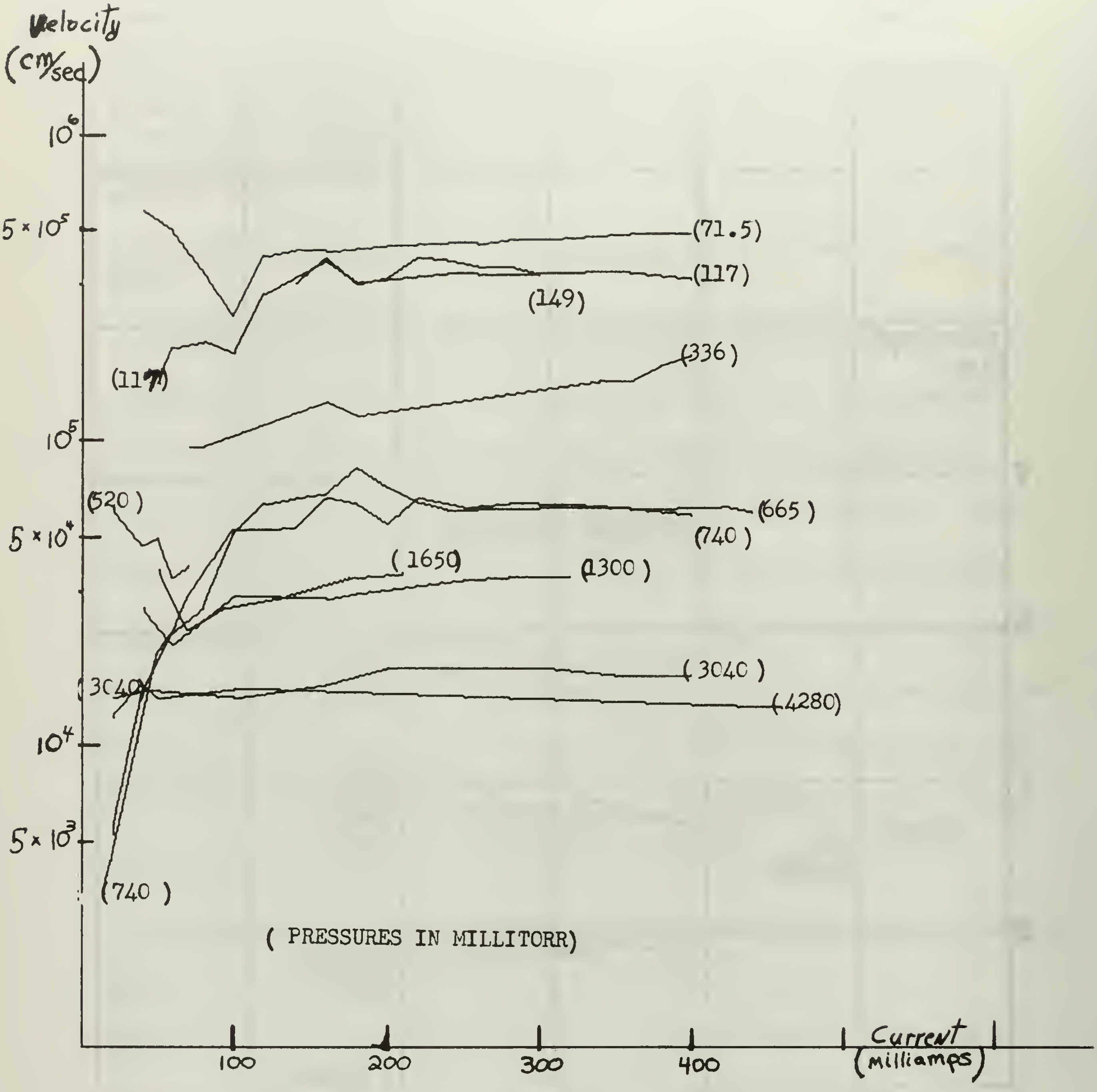


Figure 13. Striation velocity versus discharge tube current. 31 millimeter discharge tube, common pressure curves.

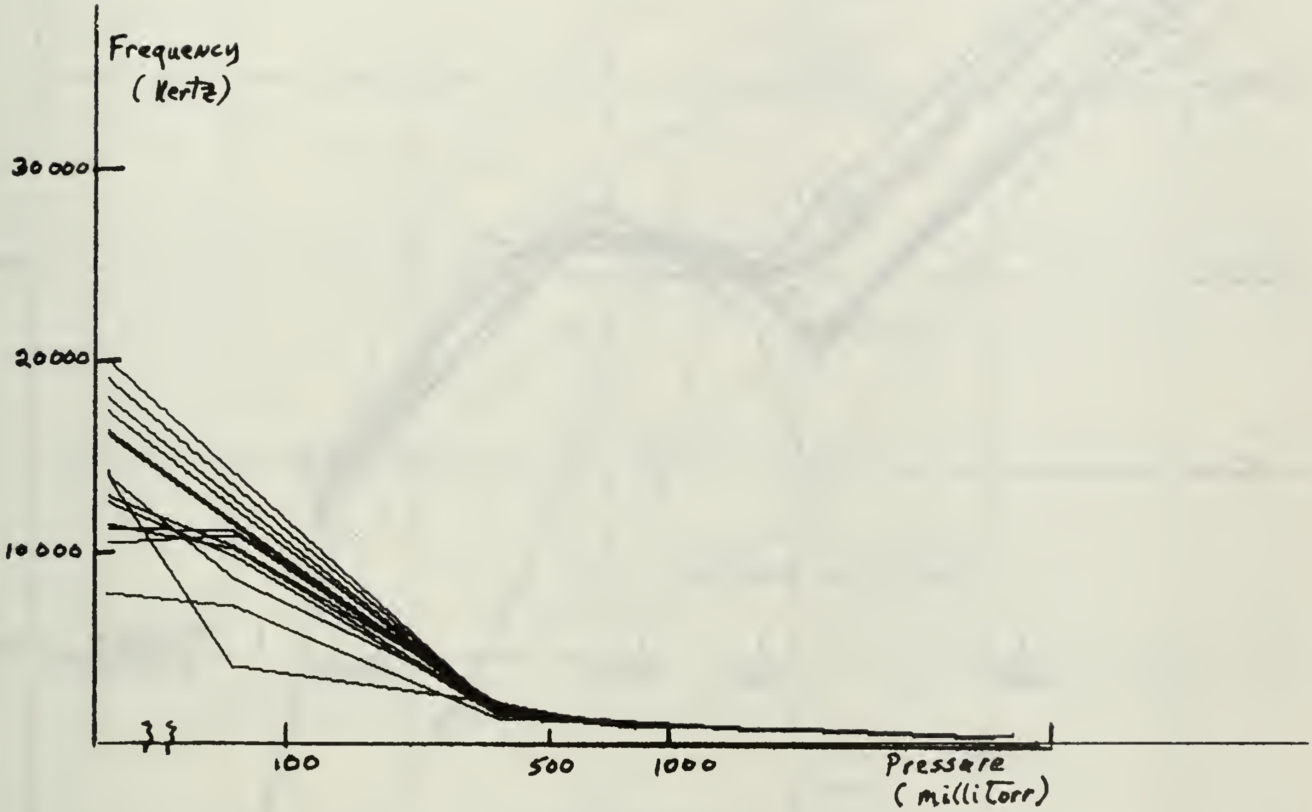


Figure 14. Striation frequency versus pressure.
75 millimeter discharge tube, common current curves.

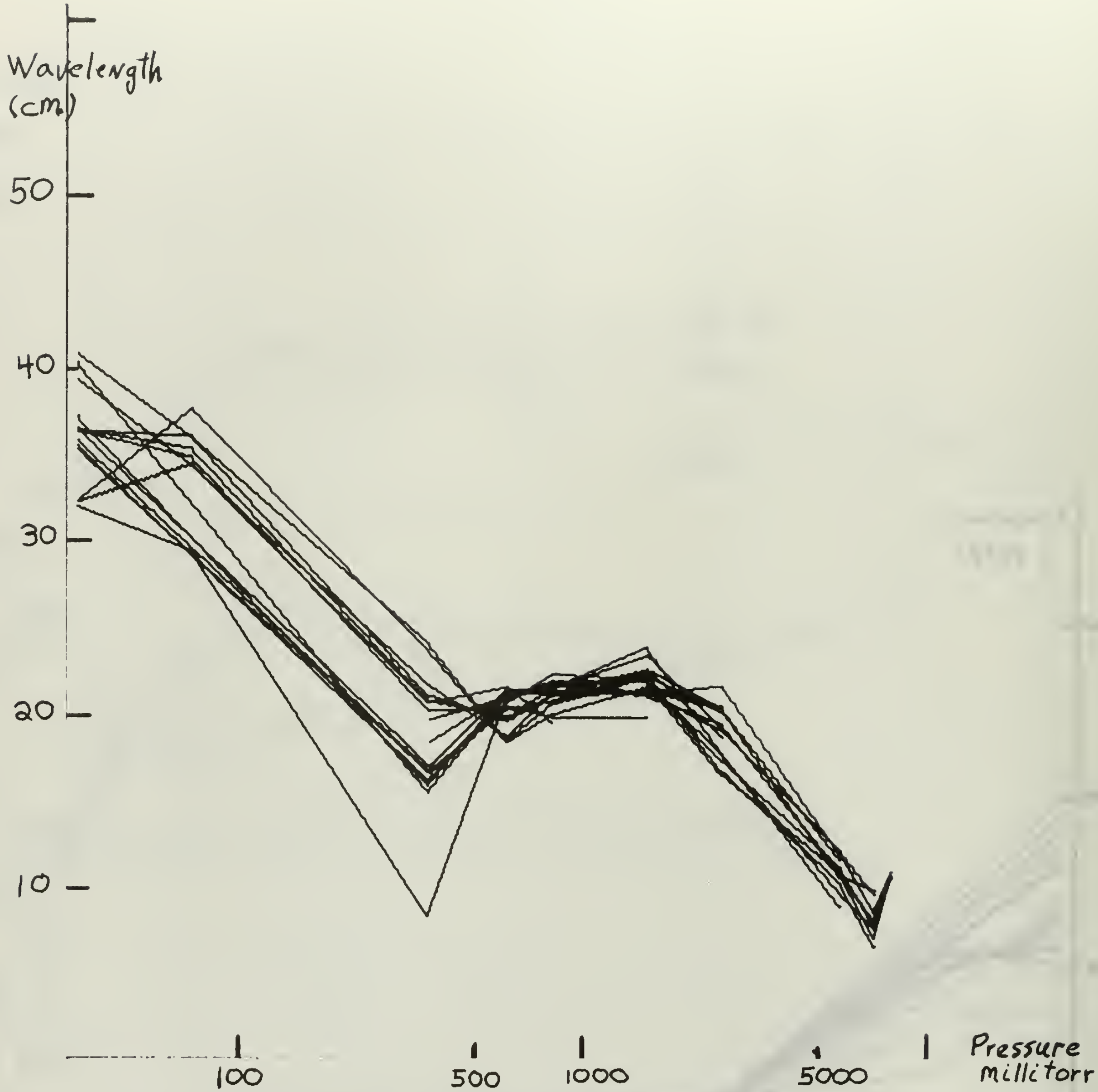


Figure 15. Striation wavelength versus pressure.
75 millimeter discharge tube, common current curves.

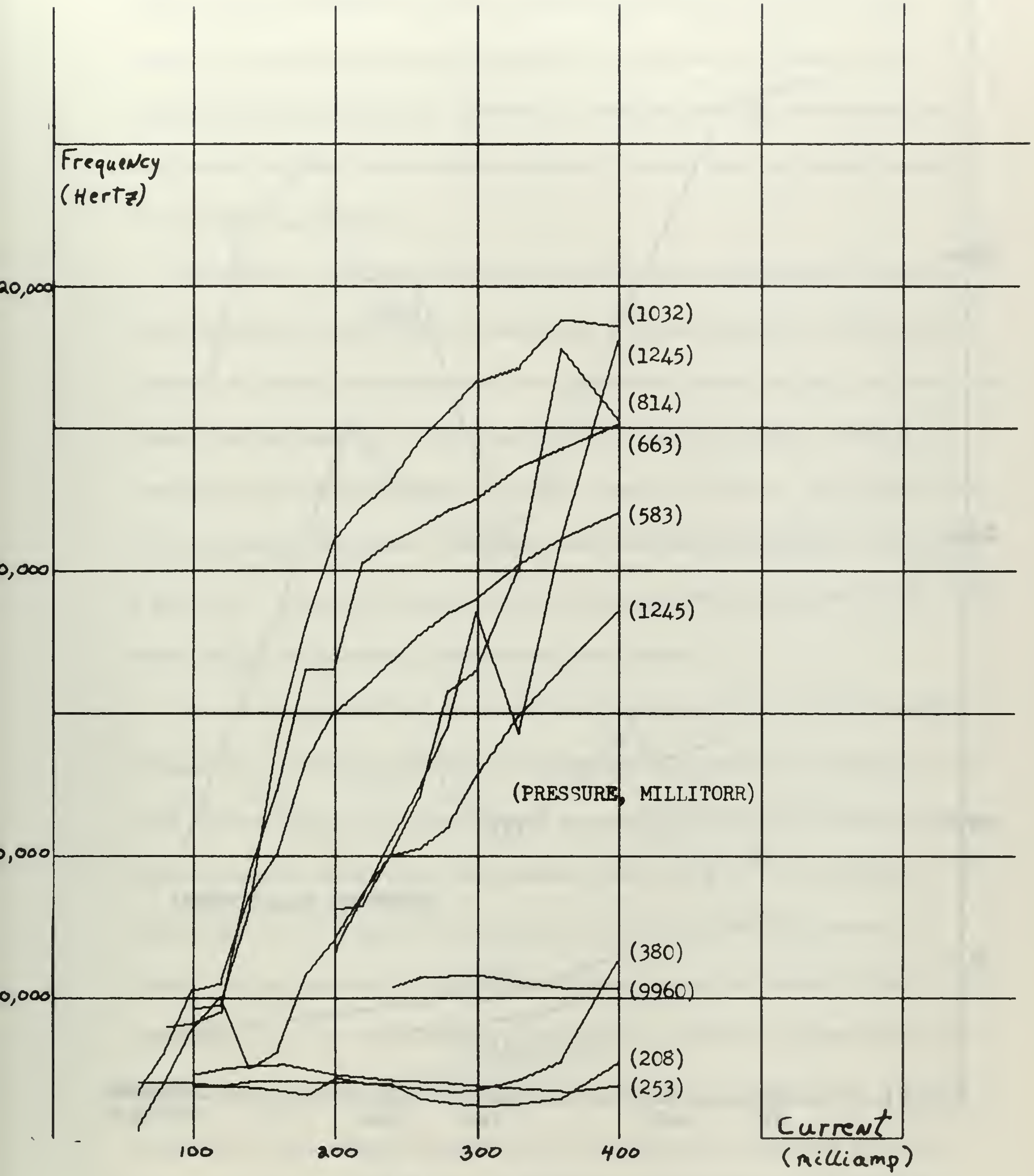


Figure 16. Striation frequency versus current.
4 millimeter discharge tube, common pressure curves.

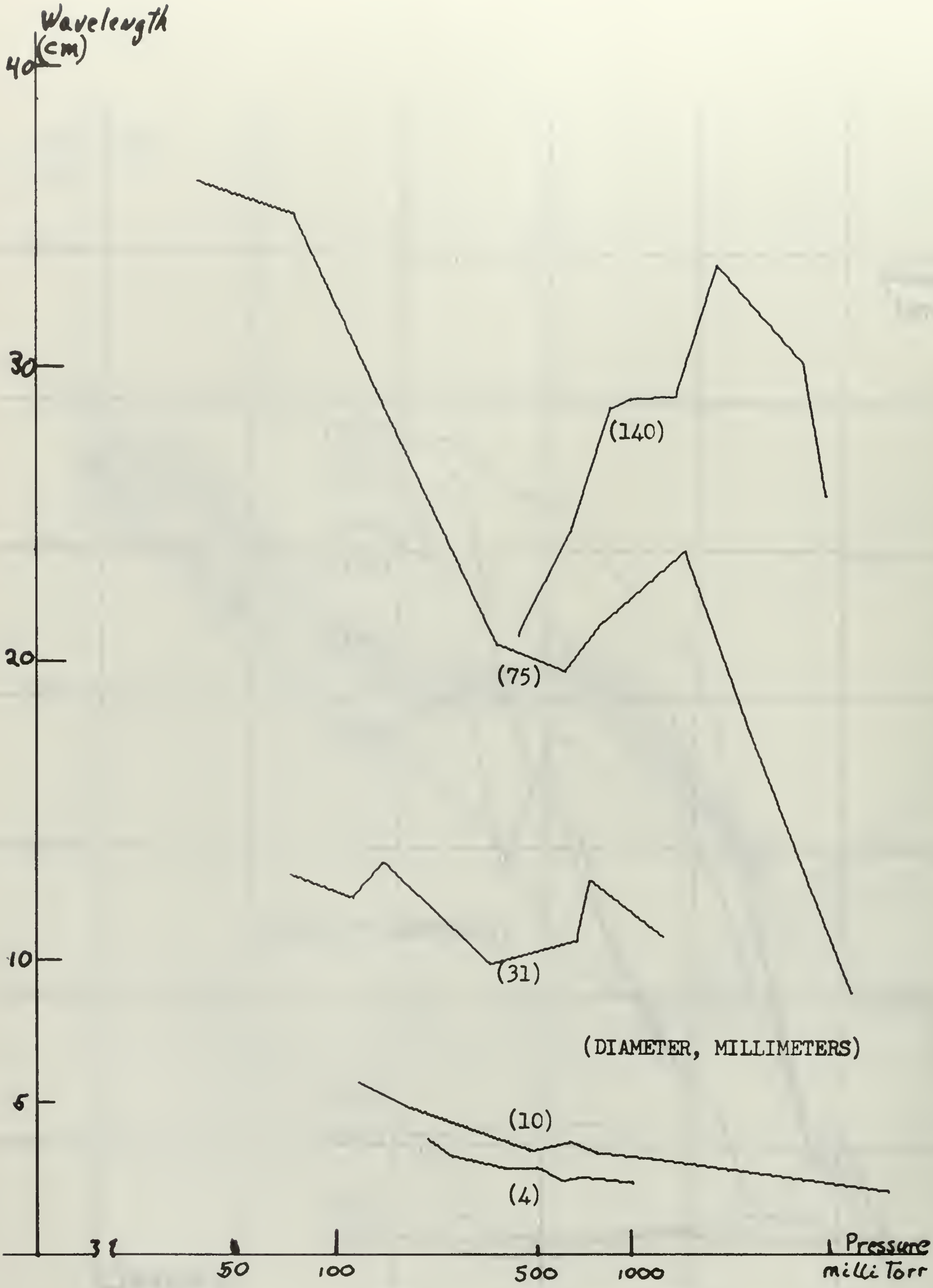


Figure 17. Striation wavelength versus pressure.
Data from all discharge tubes for 180 milliamps current.

(All of this graphic output of data made it easy to see how earlier investigators who took data in these central regions had arrived at their empirical equations relating dependent variables to only one or two independent parameters.) However, coherent moving striations are also found outside these middle regions; here, data no longer seems to fit these equations.

Therefore, the final analyses involved the relationships between the mathematical products of variables. Most frequently used as independent variable combinations were pressure times radius, and pressure times current density. It should be noted that the latter, $pi/\pi R^2$, combines all the independent variables into one factor. An example of how dependent variables relate to these defined parameters is shown in Figure 18. In general these relationships proved to be more linear than when single independent parameters were used.

It was suggested that the well-known parameter, current density, be used in an attempt to relate the dependent variables. However, the $1/R^2$ factor in this variable caused exceedingly little data taken with one tube to overlap data taken with another when $i/\pi R^2$ is calculated. In this study, $1/R^2$ ranges in value from 1/4 to 1/4900 millimeters^{-2}. Hence, to get appreciable overlap between tubes in current density, the discharge current would have to range over a factor of about 1000 also.

Since the mathematical product, pressure times current, ranged over a factor of 2000 in this work, the artificial parameter pressure times current density was used. In this way, correlation between the discharge tubes at the microscopic level could be had.

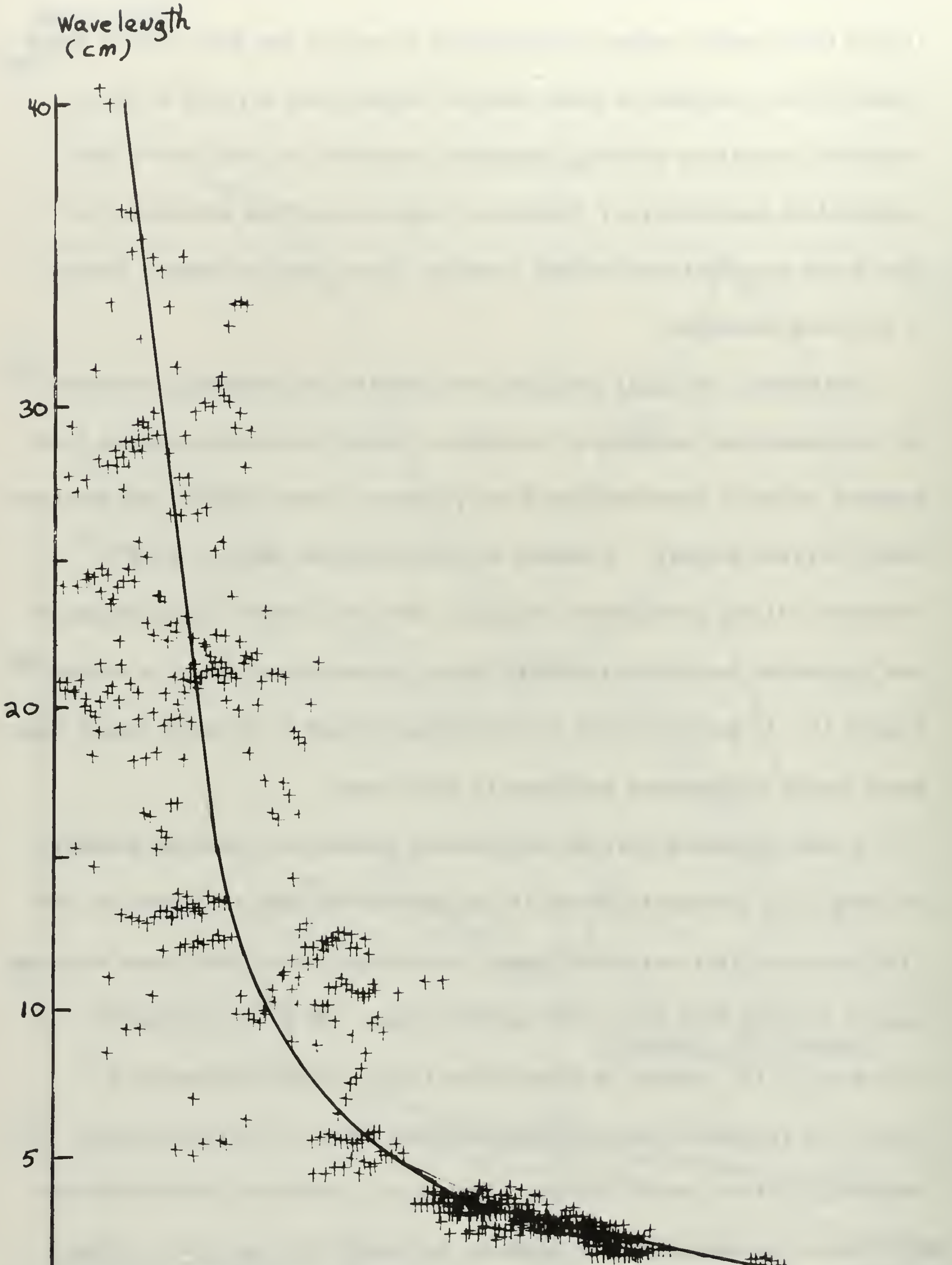


Figure 18. Striation wavelength versus pressure times current density. Data from all discharge tubes.

VI. OBSERVATIONS AND CONCLUSIONS

A. Wavelengths

The greater the tube radius, the greater the striation wavelength. This was one of the most consistent results obtained in this work. The mathematical relationship between these two factors is not at all clear, however. None the less, when wavelengths in each tube are compared under conditions of equal pressure and equal discharge current, there exists no case of a smaller tube having a wavelength greater than that of a larger tube. All attempts failed to empirically relate wavelength to radius alone.

A general conclusion reached is that striation variables are most dependent upon pressure and geometry and exhibit relatively little dependence on discharge current.

As mentioned in section II, Kenjo and Hatta derived a relationship that the wavelength was mathematically proportional to the tube radius raised to a power between 1.5 and 2.0 (5). This author also observed that their published data fitted the equation $\lambda \cong 5 \times R^N$, where N was 1.75. Certain data taken in this work agrees quite well with this equation when compared with similar pressure and current readings. However, this was true for the 10 and 31 millimeter tubes only. The equation fails badly when data from the extreme radii tubes of this experiment are applied to it.

The following chart shows these results.

experimental data		theoretical predictions
tube radius	wavelength	wavelength
1. 2 millimeters	1.8 to 4 cm (largely 2.5 to 4 cm)	0.3 cm
2. 37.5 millimeters	6.5 to 40 cm (largely 15 to 25 cm)	48 cm

Hence, one can only conclude that the constant of proportionality, K, is in fact not a constant. It seems more likely, however, that the "basic" relation $\lambda \propto R^N$, $(1.5 \leq N \leq 2.0)$, is faulty.

The wavelength seems sensitive to radius for radii between 5 and 37.5 millimeters. If the logarithms of wavelength and radius are plotted holding the pressure and current constant, a sigmoidal curve is usually obtained. Such a plot is shown by Figure 19. Unfortunately, even here one cannot empirically determine an equation of the nature $\lambda = f(R)$, because this graph is valid only for a particular combination of current and pressure. Changing either of these parameters changes the slope of the curve and hence a more appropriate relation would be $\lambda = F(p, i)f(R)$. However, for all pressures and currents of this work, the general sigmoidal nature of the relation is preserved.

As noted earlier, wavelength is rather independent of current if we use it as the sole independent parameter. Only currents less than 100 milliamps had a noticeable effect on wavelength; in that region wavelength increases with current.

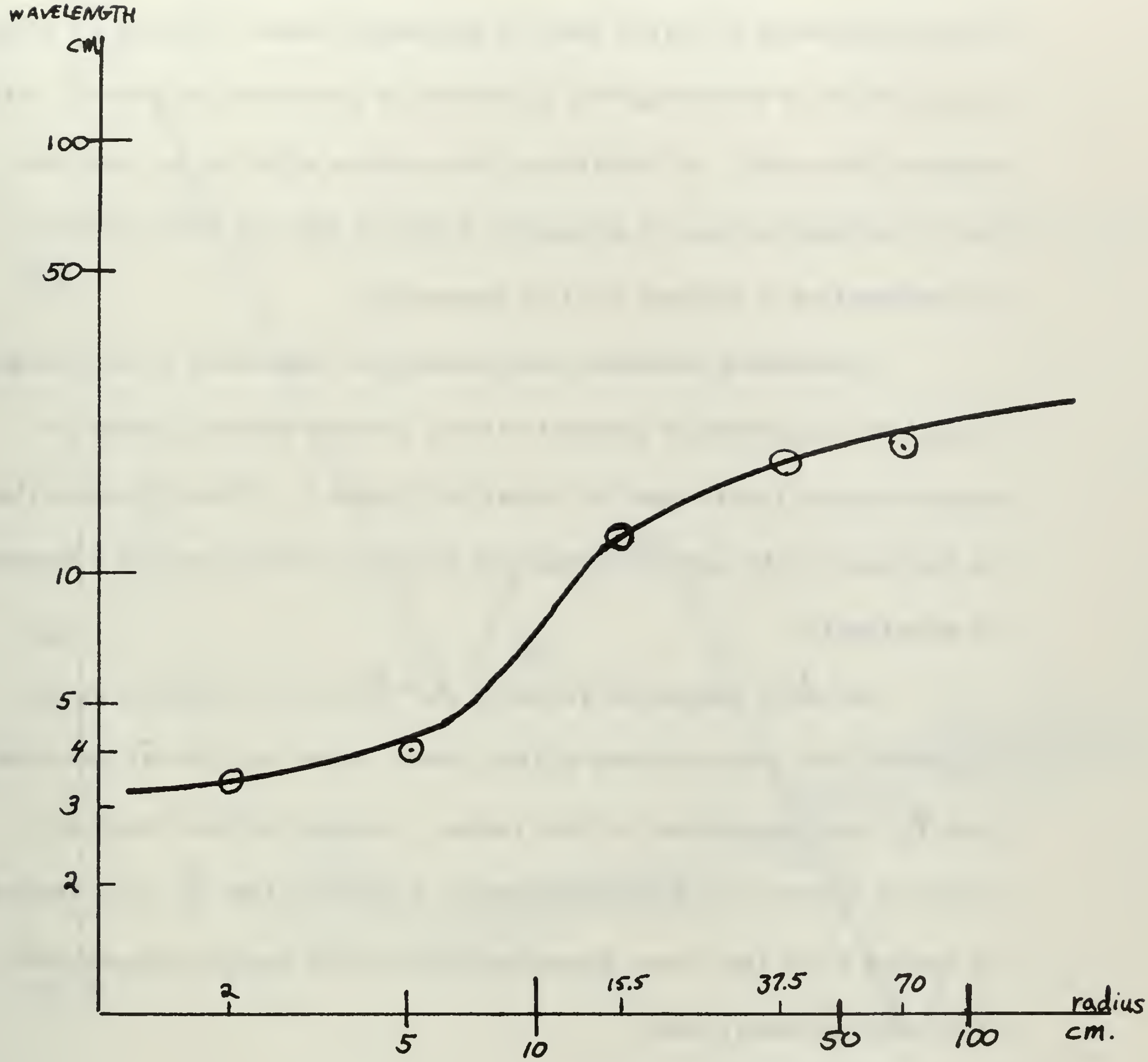


Figure 19. Striation wavelength versus discharge tube radius. Typical curve obtained from data of equal current and equal pressure.

Pressure, as the sole parameter, seems to have the most pronounced and uniform effect on wavelength. As is shown in Figure 17, increasing the pressure decreases the wavelength, the effect being more pronounced at larger radii of discharge tubes. Figure 20 shows mean effects of wavelength as a function of pressure for several of the tubes in this work. Of interest is the reverse effect to be seen with the 75 millimeter tube at pressures between 300 and 1000 millitorr. No explanation is offered for this happening.

Combining variables and plotting the logarithm of wavelength versus the logarithm of pressure times current density yields an approximately linear band as shown in Figure 21. This indicates that an increase in the pressure-current density variable causes a decrease in wavelength.

Novák's empirical relation $\lambda = \phi_i/E$, was found to agree somewhat with observations in this study. However, Novák specified that ϕ_i was independent of tube radius. Results of this study are shown in Figure 22. From this graph it appears that ϕ_i may depend on radius since the linear groupings to be noted each represent data from one discharge tube.

B. Striation Frequencies

Frequency, in general, increases as the tube radius decreases. However, no mathematical relation between these two alone was found. Throughout this phase of the study, all trends and relationships were well behaved with the exception of those resulting from the 4 millimeter

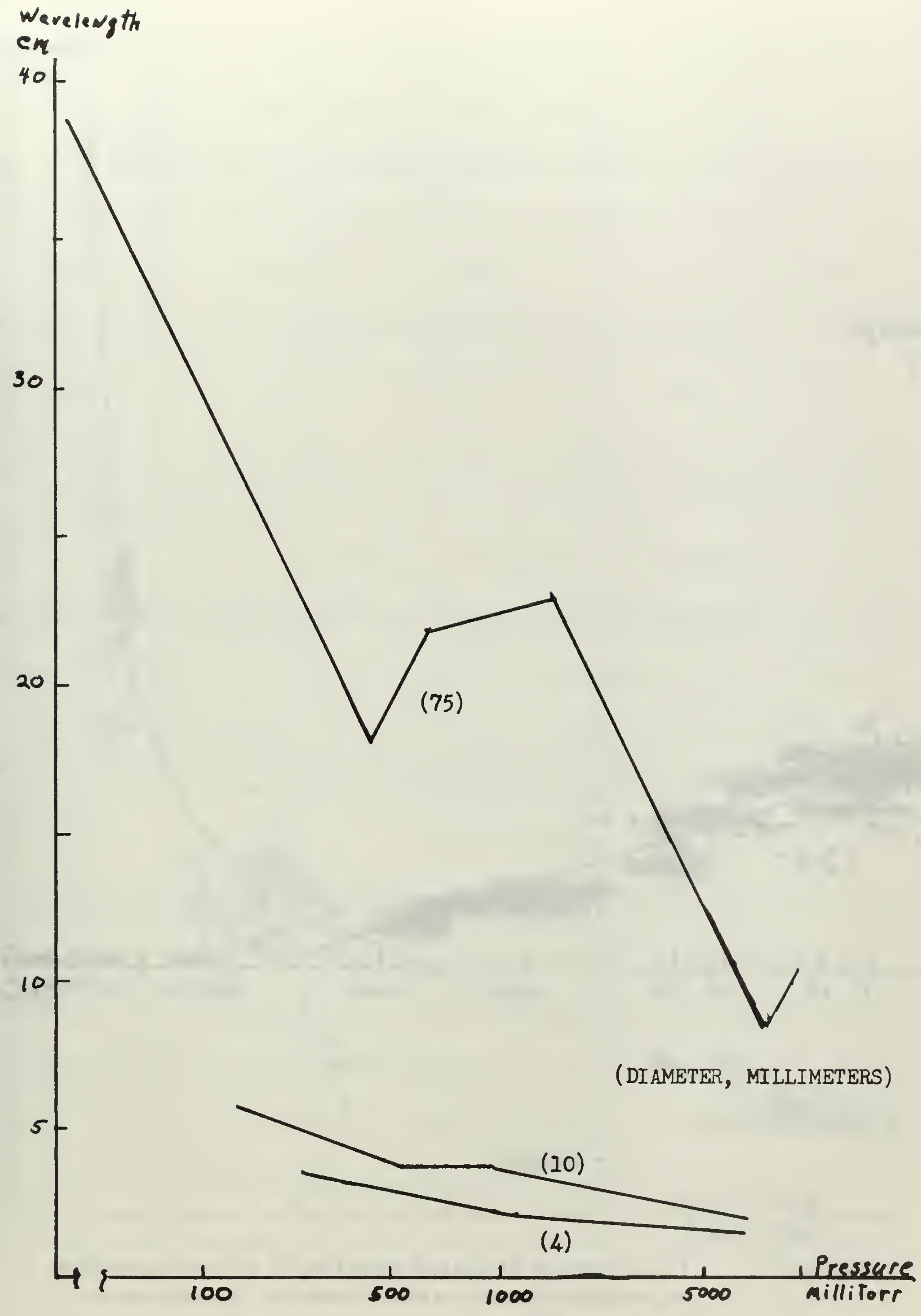


Figure 20. Striation wavelength versus pressure. Data averaged over all currents for the indicated discharge tubes.

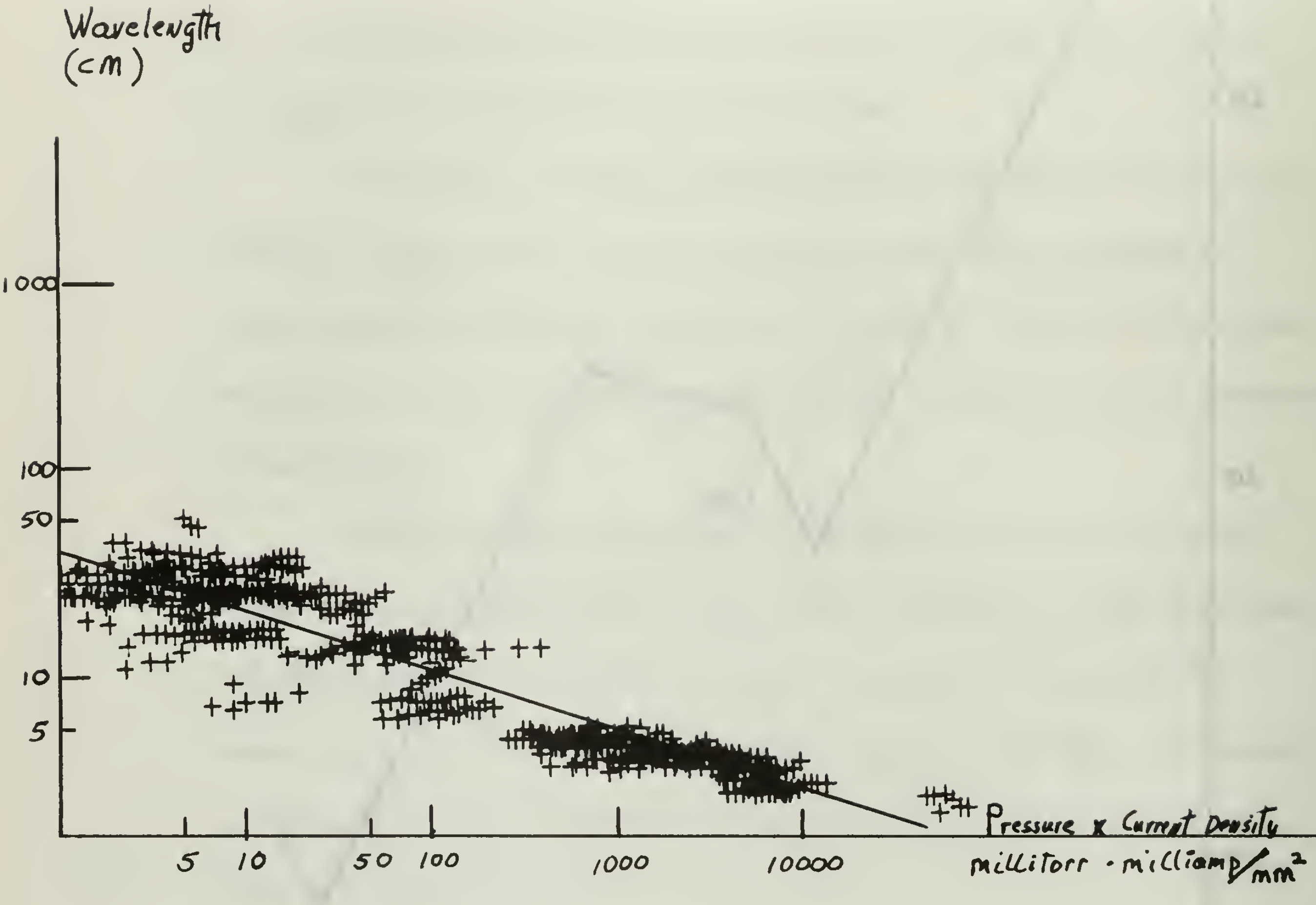


Figure 21. Logarithm of striation wavelength versus logarithm of pressure times current density. Data from all discharge tubes.

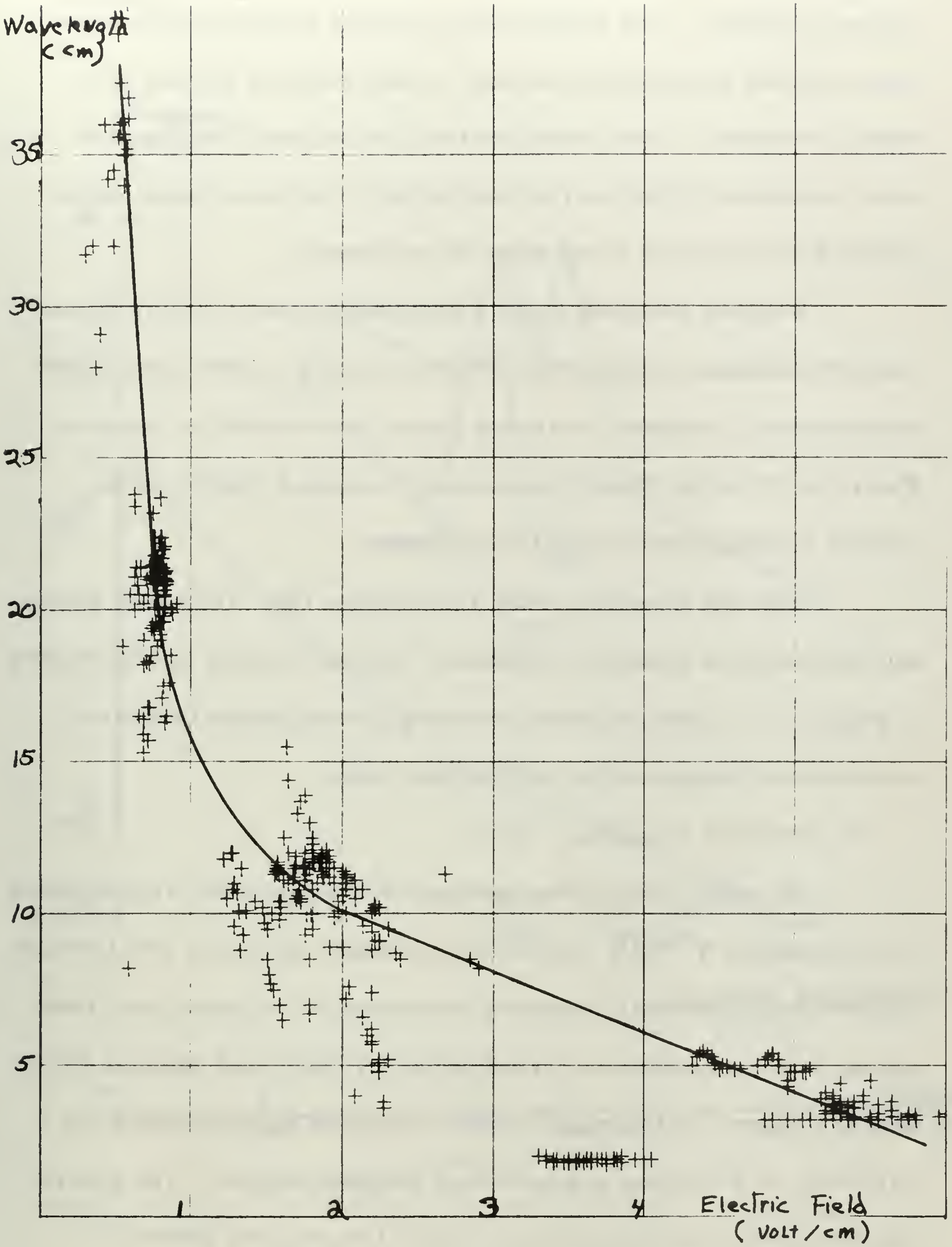


Figure 22. Striation wavelength versus electric field.
Data from 10, 31.75 millimeter discharge tubes.

discharge tube. The erractic nature of its behavior is obvious in Figures 16 and 23. The frequencies measured in the 140 millimeter tube remained remarkably constant: always between 300 and 750 Hertz. However it was noted that the glow discharge in this tube never completely filled out the tube radially, the mean radius of the visible glow discharge being about 50 millimeters.

With the exception of the 4 millimeter tube, currents greater than 100 milliamps had no effect on the frequency. In the case of that tube however, frequency increases greatly with current as shown in Figure 16. For the others, frequencies increased slightly as the current increased from 20 to 100 milliamps.

With the exception of the 4 millimeter tube, frequency generally decreased as pressure increased. Typical findings are illustrated in Figure 23. Figure 24 shows the mean (averaged data) effects of pressure on frequencies for all the tubes used.

C. Striation Velocities

Striation velocity was not measured directly but was computed by the equation $V = \lambda \nu$. Because wavelength increased with increasing tube radius whereas frequency decreased at the same time, there was no clear cut relation or trend between velocity and radius. This finding is shown by Figure 25, which illustrates typical results for velocities as a function of pressure at constant current. The generalization made in earlier studies (5 and 7) that velocity generally increased as tube diameter decreased cannot be supported by this work.

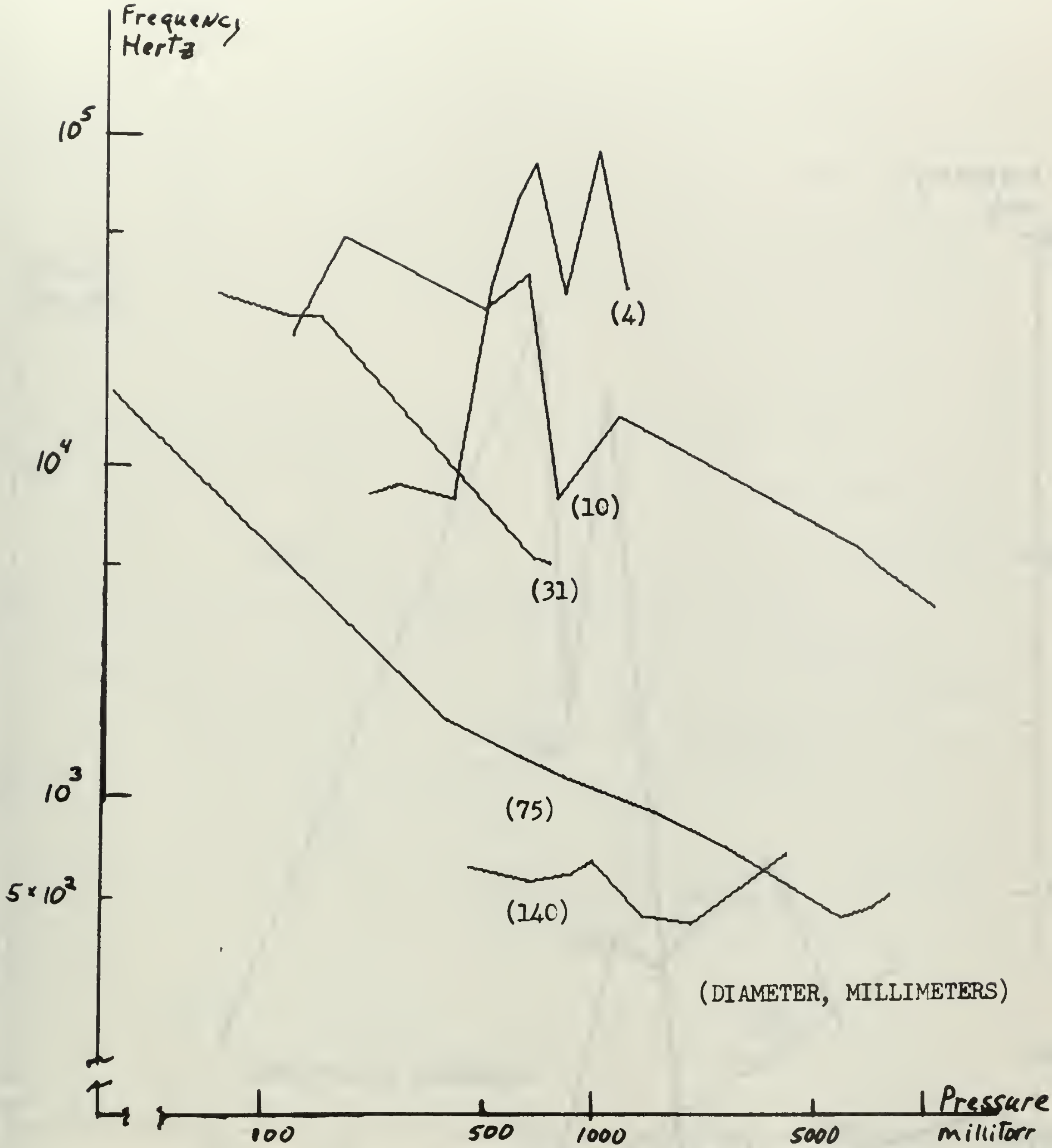


Figure 23. Striation frequency versus pressure.
Data from all discharge tubes for 220 milliamps current.

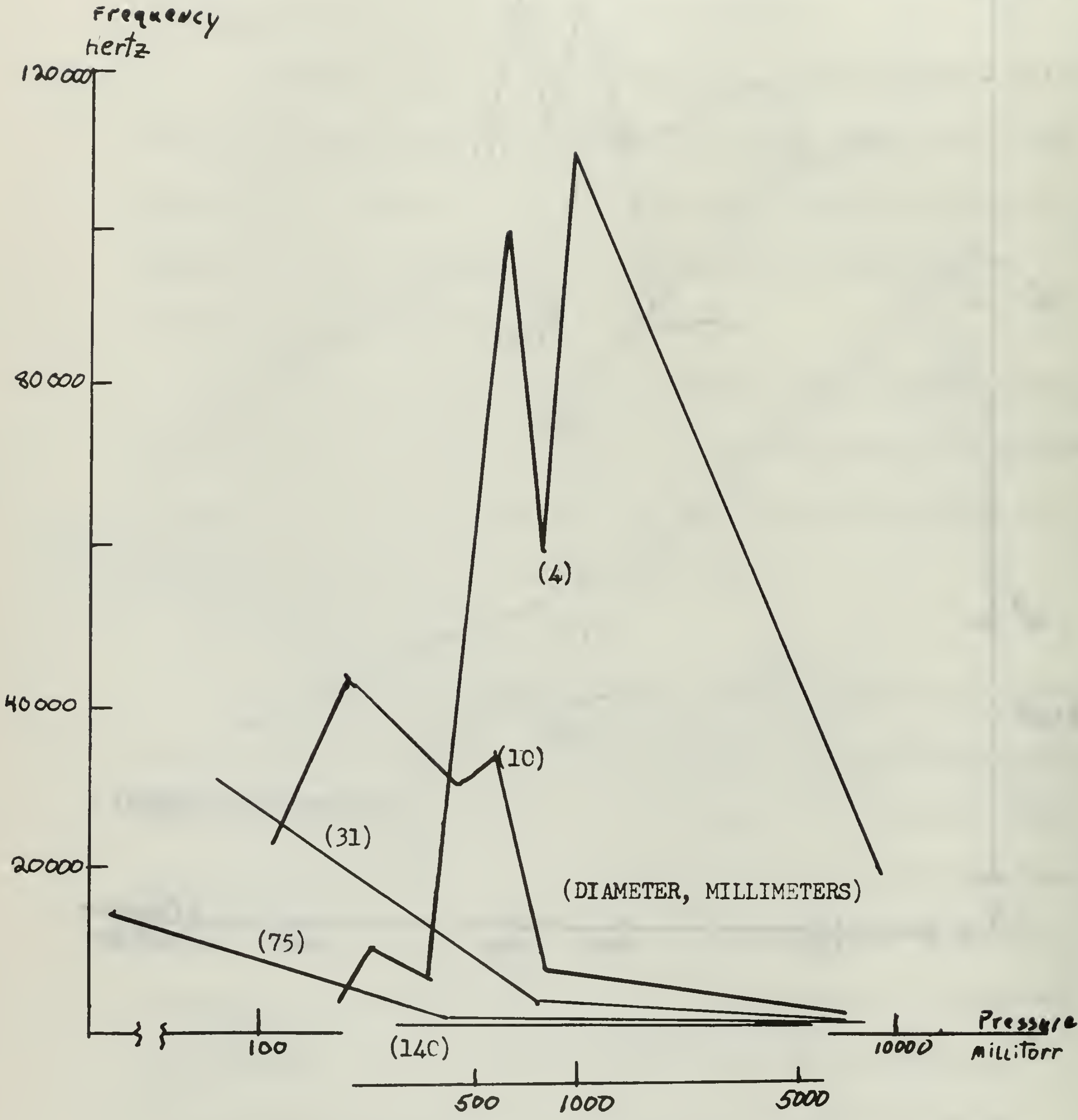


Figure 34. Striation frequency versus pressure. Data averaged over all currents for the indicated discharge tubes.

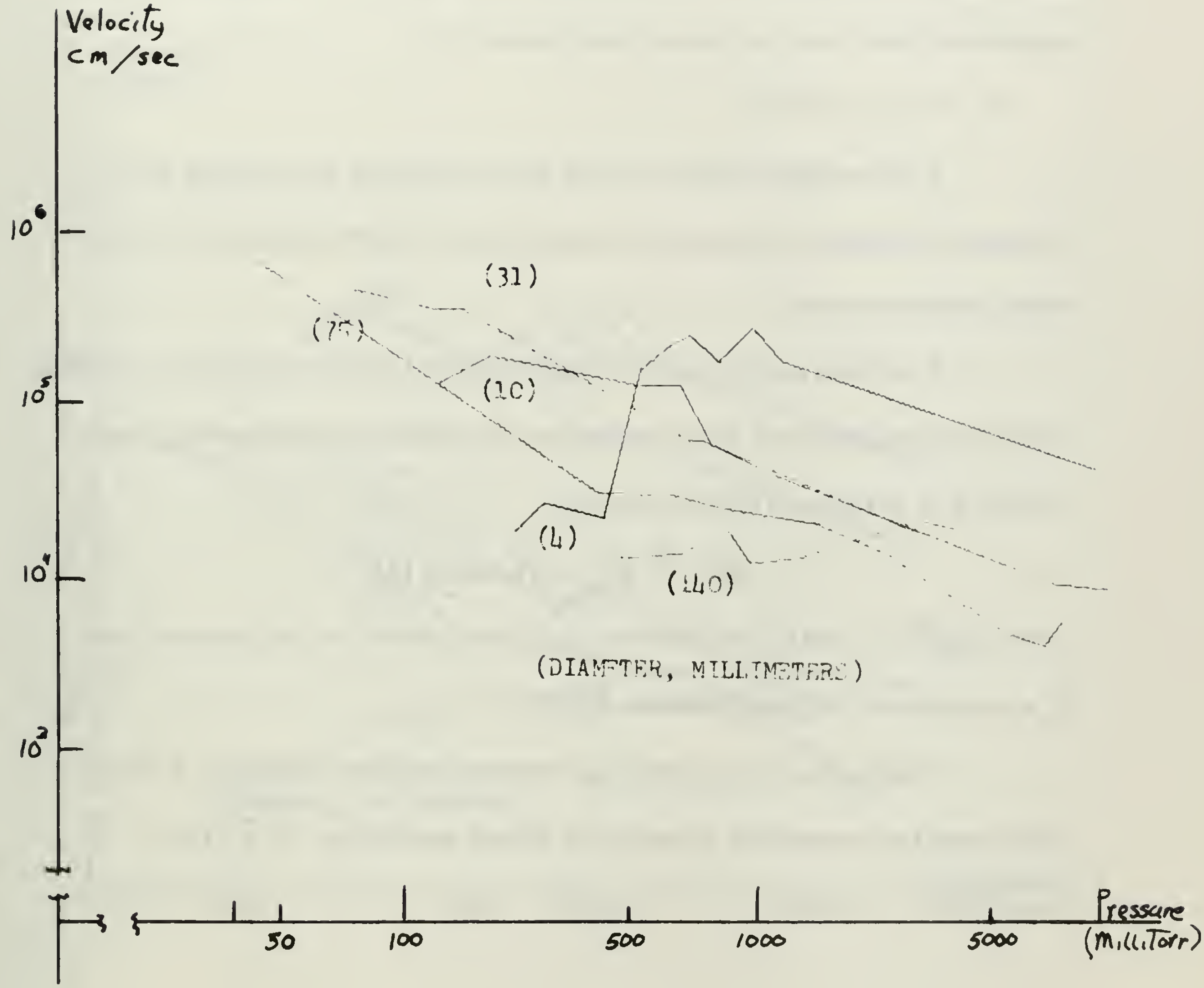


Figure 25. Striation velocity versus pressure.
Data from all discharge tubes for 300 milliamps current.

Currents greater than 100 millimaps had no effect on velocity; it remained quite constant above this value. Between 20 and 100 milliamps, velocity generally increased with current. This result follows from the same effect observed between frequency and current.

As pressure increased, velocity decreased and this trend is shown in Figures 25 and 26. Figure 26 represents the mean (averaged data) effect of pressure on velocity for all tubes. This finding is in agreement with that of Alexeff and Jones (6).

D. Electric Field

The average electric field was computed by dividing the voltage difference measured between the two fixed probes by the distance between them.

For pressures on the order of 2000 millitorr and less, it was found that the electric field decreased linearly with increasing radius, seeming to follow a relation give by

$$E \cong E_0 - K \operatorname{Log}(R) \qquad 4.$$

where $E_0 \cong 8.0$ volts/centimeter, R is the radius in millimeters and K a constant of proportionality $\cong 4.5$.

There was no general agreement between findings of this study and the empirical equation of Kenjo and Hatta, $E \cong 4/R$.

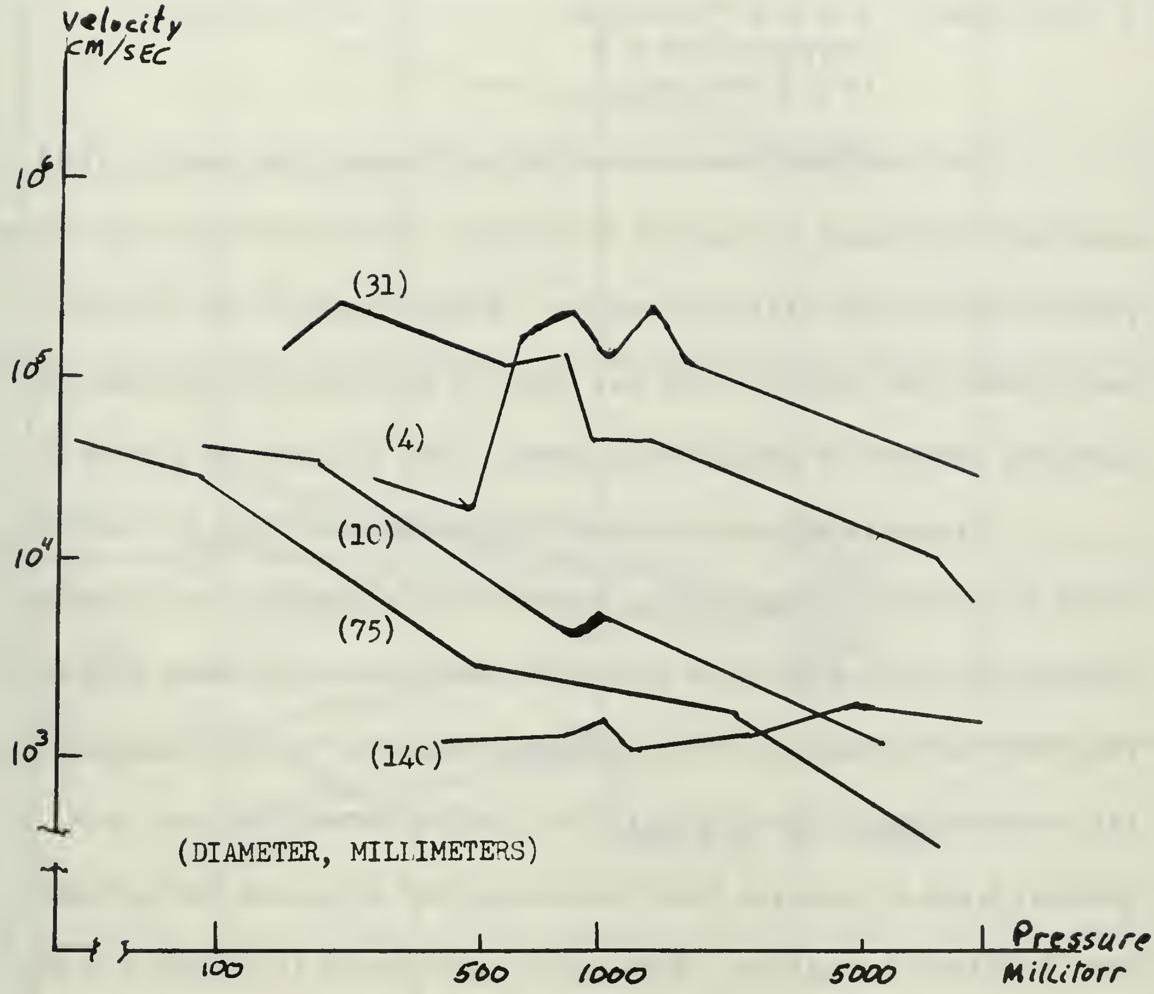


Figure 26. Striation velocity versus pressure. Data averaged over all currents for the indicated discharge tubes.

Applying this relation we find:

experimental data		theoretical prediction
tube radius	electric field	electric field
1. 5 mm	3.3 to 6 volt/cm (largely from 4 to 6 volt/cm)	8 volt/cm
2. 15.5 mm	1.3 to 2.8 volt/cm (largely from 1.5 to 2 volt/cm)	2.6 volt/cm
3. 37.5 mm	0.3 to 1.7 volt/cm (largely from 0.5 to 0.9 volt/cm)	1.05 volt/cm

For currents greater than 100 milliamps, the electric field generally decreases as current increases. This effect becomes more pronounced as tube radius decreases. Surprisingly in the 75 millimeter tube, the electric field was found to increase with current for currents between 20 and 100 milliamps. This is shown in Figure 27.

Pressure affects the electric field but there was no uniform trend to be noted, much less an indication of a mathematical relation between the two. Figure 28 shows the mean (averaged data) effects of pressure on the electric field. Güntherschulze's "normal gradient" (8), was notfound. From Figure 28 it can be noted that there is a general trend of electric field increasing with pressure until about 1000 millitorr is reached. After that, it continues to increase in the case of the 75 millimeter tube but decreases in the others.

E. Probe Perturbations

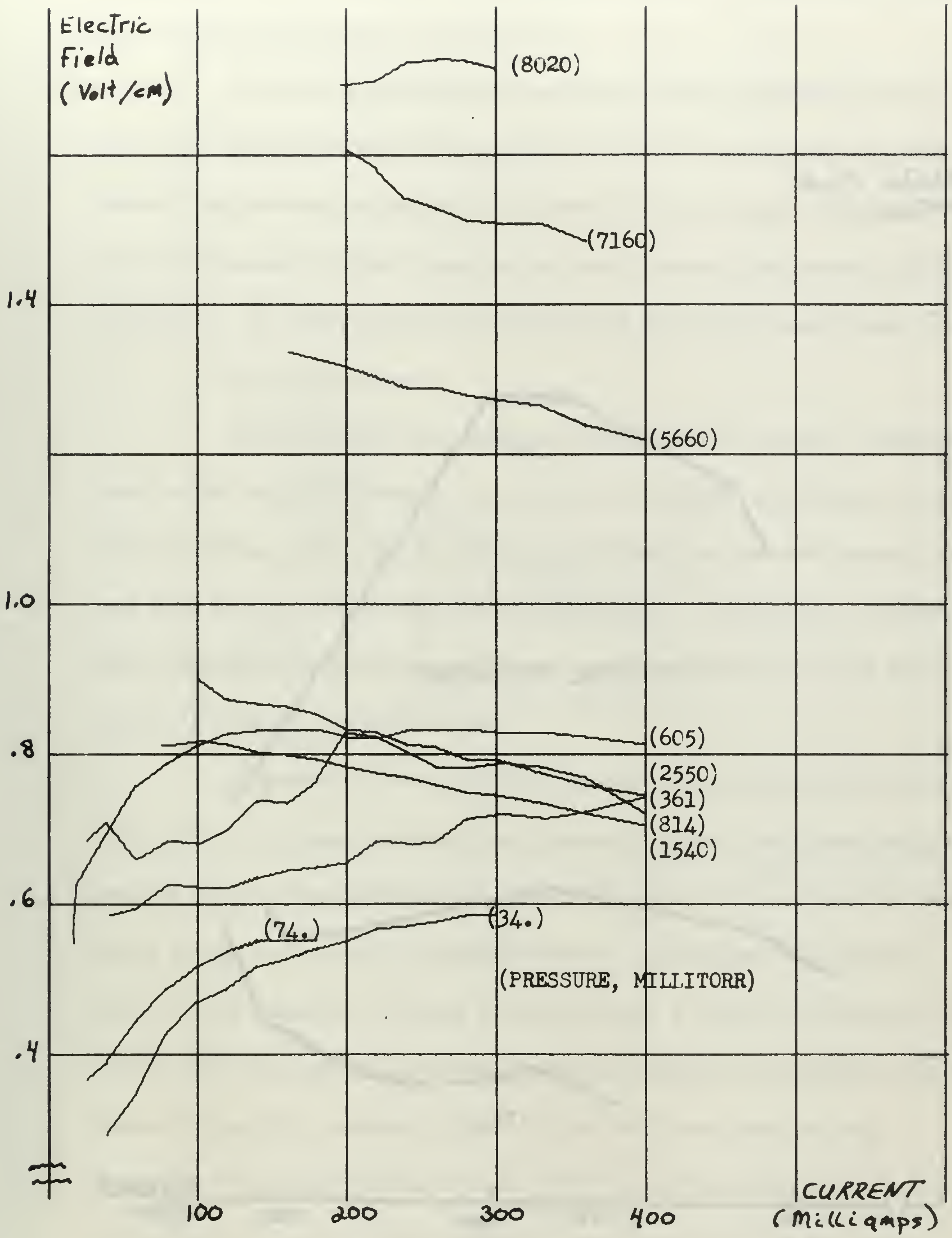


Figure 27. Electric field versus current.
75 millimeter discharge tube, common pressure curves.

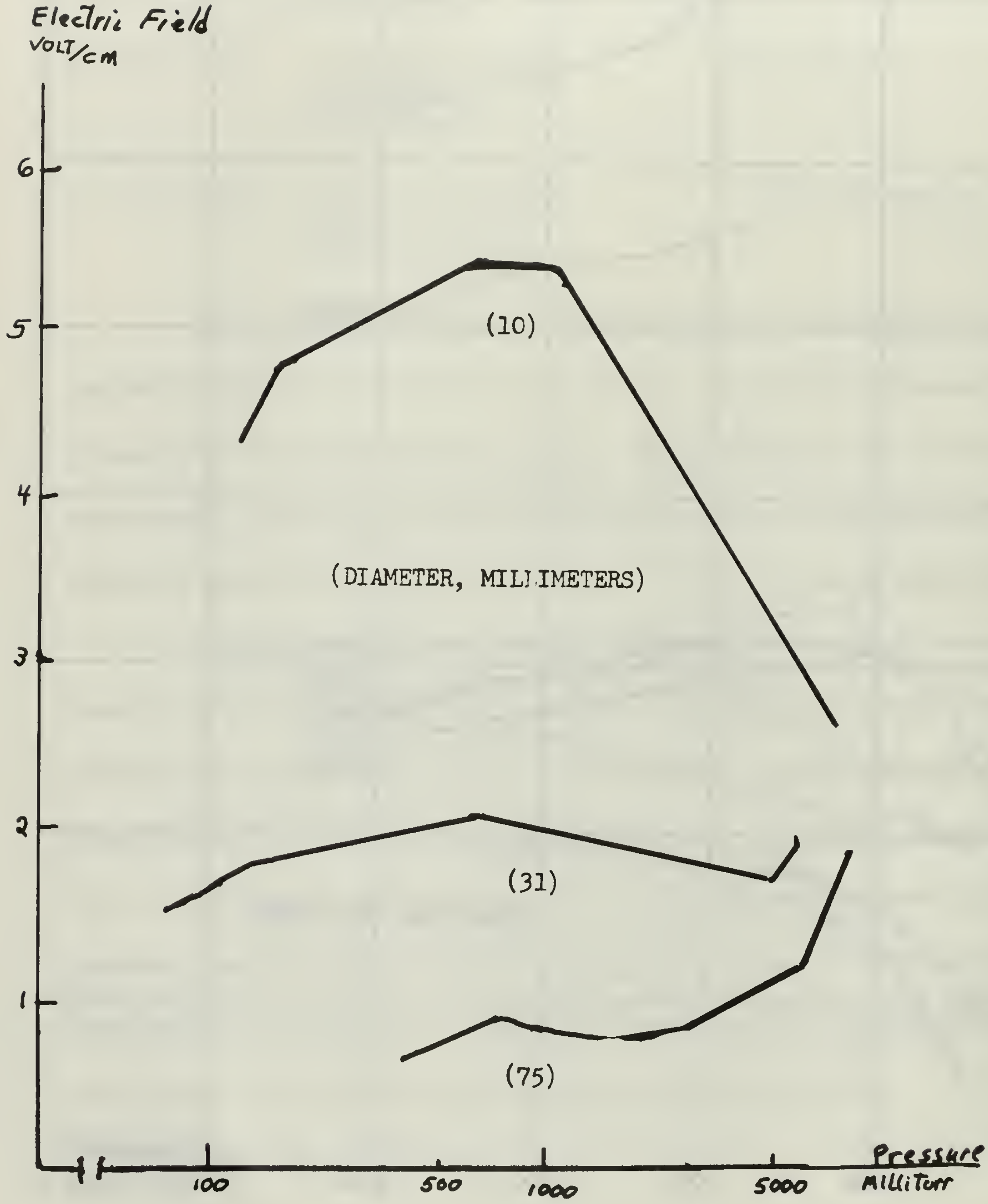


Figure 28. Electric field versus pressure. Data averaged over all currents for the indicated discharge tubes.

It was observed that probes generally decrease both the frequency and wavelength of the moving striations, this effect being more pronounced at lower pressures.

At about 1000 millitorr pressure, the velocities of striations in a discharge tube with probes are about 20 percent less than those of striations propagating in a tube without probes. This difference decreases to about 1 percent as the pressure increases to 1000 millitorr. At high pressure no significant difference was found.

F. Final Comments

In analysing the graphs to obtain best-fit curves, allowances were made for point density at certain locations on the figure. In the offset printing of this study, these high density areas will appear black and data points within them will be indistinct. Conversely, distinct, well-separated data points represent a minute portion of total data: typically 1 point out of 500 total.

In general it was found that most of the unusual behavior came in the extreme pressure and radius regions when those two parameters were simultaneously in effect. Several of the graphs in this study illustrate this by showing a cluster of points off the mean fit curve. For example, Figure 22 shows such a cluster in the area of 3 to 4 volt/centimeter along the electric field axis and about 2 centimeters along the wavelength axis. This data was taken at high pressure in a small diameter tube (7500 to 10,000 millitorr, 10 millimeter tube). On the same figure the very few points on the upper left

portion of the curve (wavelength of 30 to 40 centimeters) are from the 75 millimeter tube operated at pressures of 35-75 millitorr.

Good correlation between Pupp's work and this were found. Figure 29 shows all the data taken in this work plotted as radius times frequency against radius times pressure. However, the data clearly fits a hyperbolic band of finite thickness rather than falling on one smooth curve, as observed by Pupp. Most of this added width is due, again, to data taken at pressure and radii extremes.

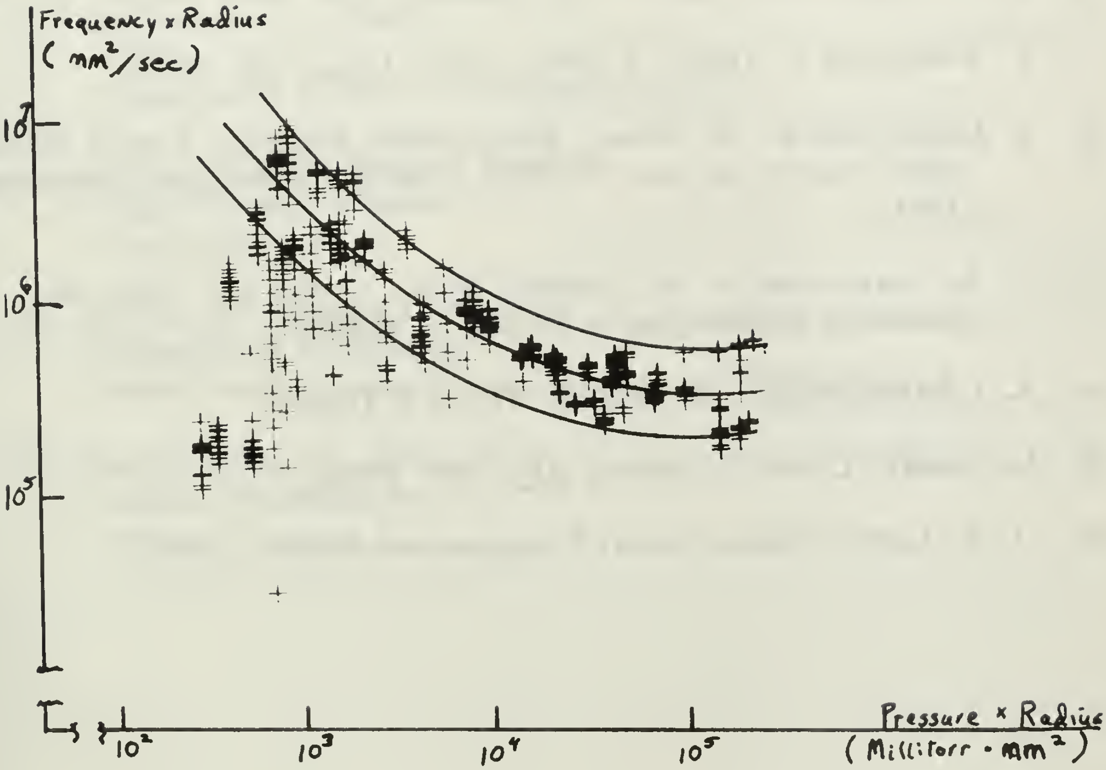


Figure 29. Frequency times radius versus pressure times radius. Total data from this study.

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13. ABSTRACT Wavelengths and frequencies of self-excited moving striations in the plasma of a Neon discharge were measured; from this data their velocities were calculated. Measurements were performed in cylindrical Pyrex discharge tubes of inner diameters 4, 10, 31, 75, and 140 millimeters over a pressure range of about 35 to 10,000 millitorr and a discharge current range of about 20 to 400 milliamps. In the 10, 31, and 75 millimeter tubes the average electric field of the plasma was measured under these same conditions. Wavelengths always increased with tube radius, generally decreased as pressure increased, appeared independent of current, and showed an exponential decrease as a function of the parameter, pressure times current density. With the exception of the 4 millimeter discharge tube, frequency generally decreased as radius or pressure increased and appeared relatively insensitive to current changes; in that tube frequency patterns were often eratic. Velocity decreased with pressure and seemed unrelated to radius or current. The electric field decreased linearly with the logarithm of increasing radius, generally decreased as current increased and followed no consistent pattern with pressure. Probes inserted into the plasma for electric field measurements generally caused both striation wavelength and frequency to decrease.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Neon striation wavelength						
Neon striation frequency						
Neon striation velocity						
Neon plasma average electric field						